

MARINE-ENTRY TIMING AND GROWTH RATES OF JUVENILE CHUM SALMON IN  
ALASKAN WATERS OF THE CHUKCHI AND NORTHERN BERING SEAS

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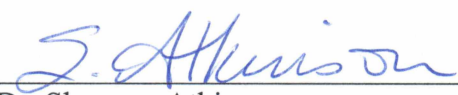
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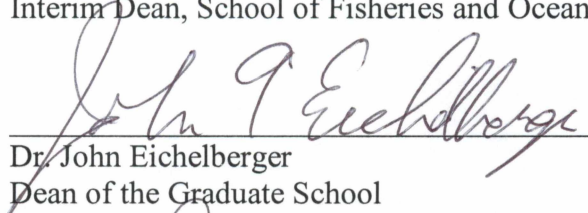
  
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THESIS

Presented to the Faculty  
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By

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## Abstract

Recent climate change is most pronounced in the Arctic, with many implications for juvenile salmon life-history patterns, such as altered timing of migrations and/or timing and success of life-history stages. The objectives of this study were to determine the timing of marine entry and early marine growth of juvenile Chum Salmon *Oncorhynchus keta* in the Chukchi and northern Bering seas. Sagittal otoliths were collected from juvenile Chum Salmon in summers 2007, 2012, and 2013 via surface trawls in the southern Chukchi and northern Bering seas. Inductively coupled plasma-mass spectrometry (ICP-MS) was used to discriminate between freshwater and marine environments, and daily growth increments were counted to determine marine-entry dates and growth rates of juvenile Chum Salmon to make temporal and regional comparisons of juvenile characteristics. Marine-entry dates ranged from mid-June to mid-July, with all region and year combinations exhibiting similar characteristics with respect to entry timing, i.e., larger individuals at the time of capture entered the marine environment earlier in the growing season than smaller individuals. Juvenile growth rates were estimated to be, on average, 4.9 % body weight per day in both regions in summers 2007 and 2012, and 6.8% body weight per day in the Chukchi Sea in 2013. This study shows consistent conditions among regions with respect to juvenile Chum Salmon marine-entry timing, with some variation in growth rates. These results provide a novel and more thorough evaluation of juvenile Chum Salmon early life-history characteristics in the Alaskan Arctic and provide a baseline for comparisons with future climate change studies.



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## **General Introduction**

Growth is a critical process for all fish life-history stages and is influenced by many biotic and abiotic factors. Growth can be observed in fish by an increase or decrease in length, weight, mass, or volume, as well as other physiological indices (Weatherley and Gill 1987). For juvenile fish, growth can be defined as the energy gain equal to  $C - (F + U) - R$ , where  $C$  is the energy content of consumed food,  $F$  is the energy lost as feces,  $U$  is the energy lost as excretory by-products (such as ammonia and urea), and  $R$  is the energy lost as heat during metabolic processes (Wootton 1998). This relationship can be used for predictive growth models and applies only to juveniles that are not yet reproductively mature. Growth in fish is indeterminate, although growth rates decline with fish age and with varying, non-idyllic environmental conditions (Brett 1979; Weatherley and Gill 1987). Many environmental variables effect fish growth, including temperature, water chemistry, photoperiod, and food availability, as well as the physiological condition of the fish (Brett 1979; Weatherley and Gill 1995; Quinn 2005).

Water temperature is one of the most important environmental factors influencing fish growth. In general, metabolic rate and daily growth of fish increase with increasing water temperature, given sufficient food availability, which assists survival rates of some marine fish during early life-history stages (Brett 1979; Pepin 1991; Mortensen and Savikko 1993). For example, experimental studies have shown that if food is not limited, growth rates will increase up to an optimum temperature, then decline at temperatures above that optimum level (Brett et al. 1969; Ricker 1979; Salong et al. 2000; Handeland et al. 2008). Temperature affects the rate of food consumption as well as growth efficiency at a given food ration (Brett et al. 1969; Elliott 1982). At optimum temperatures for growth and an abundance of food, consumption and oxygen uptake also increase, which has been shown to increase instantaneous daily growth (Houde 1989;

Wootton 1998). Optimum temperatures are species and region specific, and may be impacted by changes in climate, especially in Arctic and sub-Arctic regions.

Temperature also has indirect effects on fish growth via its effects on prey and energy allocation. Water temperatures in rivers and oceans not only affects the metabolism of fishes, but can also influence prey quality and quantity, and predators of early life stages. For example, lipid-rich copepods in the Bering Sea are associated with cooler temperature regimes, which has implications on the availability and growth potential of higher trophic levels that feed on these copepods, such as juvenile Pacific salmon (Coyle et al. 2011; Hunt et al. 2011). Larger, faster-growing individuals with higher energy reserves are more likely to survive their first winter at sea, and variation in growth among years due to growing conditions and prey availability provides insights on specific size-selective mortality and size-dependent migration (Myers et al. 2000; Beamish and Mahnken 2001; Farley et al. 2007; Cross et al. 2008). It has been shown that juvenile salmon may grow longer with increased sea surface temperatures (SSTs), but may allocate more energy to lipid storage in cooler temperatures (Andrews et al. 2009; Prechtl 2014). These studies indicate that thermal regimes and variation in water temperatures may have significant effects on juvenile salmon life-history stages where size and growth are important for survival.

Juvenile salmon growth in marine environments is also influenced by density-dependent processes. Slower growth due to a reduction in prey resources via inter- and intraspecific competition has been shown to occur in late larval and juvenile life stages (Cowan et al. 2000). Schindler et al. (2005) examined responses between predators and prey during a warm phase of the Pacific Decadal Oscillation and found that large numbers of spawning Sockeye Salmon *Oncorhynchus nerka* due to early ice break-up had a negative effect on juvenile growth rates.

This interaction shows the complex responses that juvenile salmon and their prey potentially have in a warming climate. Although their study investigated patterns in the freshwater residency of juvenile Sockeye Salmon, this research demonstrated that such a change in climatic conditions may alter competition, and therefore survival, of Pacific salmon (Schindler et al. 2005). Beamish and Mahnken (2001) stated that climate controls the availability of nutrients regulating the food supply (i.e., bottom-up regulation) and also regulates competition for food in juvenile salmon that ultimately causes stunted growth, hormonal dysfunction, or death. High mortality during early marine residency has implications on variability in brood-year strength and adult returns (Sogard 1997; Wertheimer and Thrower 2007).

Before juvenile salmon reach the marine environment after downstream migration, they enter estuarine environments that vary in salinity (Quinn 2005). Whether estuaries serve as rearing habitat for smolts or are simply areas that fish must navigate to feed in marine waters is unknown (Simenstad et al. 1982; Quinn 2005). However, this time period is a particularly important stage in the life history of salmon, particularly Chinook *Oncorhynchus tshawytscha* and Chum Salmon *Oncorhynchus keta*, which may reside in estuaries for extended periods (Quinn 2005; Chamberlin et al. 2011). At this point in the salmon life cycle, individuals undergo smoltification, or the process of morphological, behavioral, and physiological changes that occur during a fish's adaptation to saltwater conditions as they encounter estuarine waters (Folmer and Dickhoff 1980).

Once smoltification occurs, juvenile salmon are able to transition to a full marine residency. The timing of marine entry is correlated with latitude, with earlier seaward migrations generally observed at lower latitudes (Godin 1982; Salo 1991). Marine-entry timing of juvenile salmon varies from early spring to mid-summer, and differs with not only latitude, but length of



downstream migration, timing of parental spawning, and interaction with other species as well as changes with season, size of fish, and density of outmigrants (Simenstad and Salo 1982; Salo 1991; Weatherley and Gill 1995). As described in the match-mismatch hypothesis, year classes that enter the ocean when foraging conditions are better will have higher survival (Tomaro et al. 2012), suggesting that it is important for outmigrating salmon to arrive in the ocean when conditions are optimal. Therefore, timing and growth of juvenile salmon as they enter the marine environment is of the utmost importance for the success of juvenile cohorts.

Age and growth data are fundamental in understanding the early life-history characteristics of Pacific salmon species and how biotic and abiotic changes might affect fish populations. Using otoliths to determine age, growth, and life-history characteristics of fish is a well-documented and preferred approach because these structures grow in a cyclical nature throughout the life of a fish and are considered to be insoluble, or not vulnerable, to resorption by the body (Campana and Neilson 1985; Campana 1999; Niewinski and Ferreri 1999; Brown 2000). Otoliths are calcareous structures found in the semicircular canal near the brain of teleost fishes (Campana and Neilson 1985) that function as hearing and balance structures. These structures are comprised mainly of calcium carbonate (Summerfelt and Hall 1987), and their growth is positively correlated with fish growth (Courtney et al. 2000; Walker 2013). Consecutive zones are deposited in increments, with a dark, crystalline-formed discontinuous zone and a light, incremental zone (Campana and Neilson 1985; Summerfelt and Hall 1987). Otoliths have the ability to be aged at the daily scale (Pannella (1971), thus, making it possible to observe age and growth in age-0 juvenile fish (Campana 2001). Estimating the age of a fish is an important management tool when studied in conjunction with growth and survival data, and can be determined with several simple methods.

Although it is a lethal method for estimating age, otoliths are a reliable record of the physiochemical environments of residence for a fish. Deposition of strontium (Sr) and calcium (Ca) in otoliths and the molar ratio of Sr:Ca has been shown to reflect the environmental variability at different life-history stages of fish (Zimmerman 2005; Arai and Miyazaki 2002; Arai and Hirata 2006). It is, therefore, possible to reconstruct the different environments which anadromous fish have resided in terms of salinity and temperature (Townsend et al. 1995; Friedland et al. 1998; Campana and Thorrold 2001; Arai and Miyazaki 2002; Arai and Hirata 2006; Walther and Limburg 2012). Bath et al. (2000) showed Sr: Ca ratios to be deposited in experimentally reared marine fish otoliths in proportion to ratios in ambient waters. Concentrations of trace elements found in otoliths, including isotopes of strontium, calcium, manganese, magnesium, zinc, and barium, can be determined using an inductively coupled plasma-mass spectrometer (ICP-MS). A distinctive chemical check on salmonid otoliths shows the point of marine entry, where a peak in the ratio Sr: Ca ratio is observed due to changing salinity between fresh and saltwater environments (Zimmerman 2005; Arai and Miyazaki 2002; Saito et al. 2007; Volk et al. 2010). This peak, once identified, can be observed visually as a natural check or marker in the growth history of the fish from similar regions or stocks (Summerfelt and Hall 1987; Saito et al. 2007; Murphy et al. 2009). Visual check identification is an easier, less time-consuming method for aging juvenile salmonids. In the case of Chum Salmon, juveniles enter the marine environment more immediately after emerging from streambed gravel than other Pacific salmon species, which can be visually observed in the short distance from the otolith core to the strontium peak during ICP-MS analysis (Arai and Miyazaki 2002). These growth history and daily aging studies are important for understanding life histories

of important commercial and subsistence fish populations in Alaska, such as Chum Salmon, and for the advancement of fisheries science in the region.

Chum Salmon are the most widely distributed Pacific salmon (*Oncorhynchus* spp.) species, with a North American range extending from northern California to the Mackenzie River drainage in Canada (Salo 1991). In western Alaska, adult Chum Salmon enter rivers from the ocean between May and September, with two distinct runs in the summer and fall in the Yukon River (Salo 1991). There are also summer and fall runs of Chum Salmon in the Kuskokwim River, with peak runs from August to September. Peak runs in the Alaska Peninsula occur during July and August, while runs peak in late July and early August in southcentral and southeast Alaska, respectively (Atkinson et al. 1967; Holmes 1982; Clark and Weller 1986; Gilk et al. 2009).

Following Chum Salmon fry emergence in spring (March to May), fish move immediately to estuarine habitats to feed and do not have an extended residence period in their natal streams (Randall et al. 1987; Salo 1991; Quinn 2005). Estuaries provide an environment suitable for maximum feeding capacity and growth for age-0 Chum Salmon (Quinn 2005). While in the estuarine environment, juvenile Chum Salmon feed primarily on copepods and amphipods (Salo 1991). As food availability declines in estuaries and marine plankton blooms occur in summer, age-0 Chum Salmon move further offshore and begin to grow at an exponential rate (Salo 1991; Quinn 2005). Juvenile Chum Salmon spend 2 to 5 years at sea before returning to spawn in their natal rivers (Salo 1991; NOAA 2015).

Chum Salmon play an important role in commercial, recreational, and subsistence fisheries in Alaska. They are the most monetarily valuable salmon species due to high hatchery production in Alaska, although their market price is the lowest of the Pacific salmon (NOAA

2015). The commercial harvest of Chum Salmon in Alaska in 2012 reached over 63,000 metric tons and was valued at over \$93 million USD (NOAA 2015). In the Arctic-Yukon-Kuskokwim (AYK) region, subsistence harvest of Chum Salmon is commonly the primary salmon resource available for villages in western Alaska (Wolfe and Spaeder 2009). Recent declines in other species, such as Chinook Salmon (Eggers et al. 2013), place more importance on Chum Salmon as a subsistence resource in the AYK region. Climatic conditions strongly influence the carrying capacity for Pacific salmon and may cause fluctuations in their abundance, age composition, age at maturity, and body size (Ishida et al. 1993; Helle and Hoffman 1998; Beamish and Mahnken 2001; Zavolokin et al. 2009).

Recent increases in Chum Salmon abundance in the north Pacific Ocean are thought to be due to increased hatchery production, changing climatic indices such as SST, or both (Mueter et al. 2002; Ruggerone et al. 2010). Oceanographic and climatic conditions in the Bering and Chukchi seas effect timing of ice break-up and subsequent productivity in this region of the Arctic (Stabeno et al. 2007). The amount of spring ice coverage and the timing of sea ice retreat in the Bering Sea have significant effects on algal and zooplankton blooms, and therefore, have implications on food availability and subsequent growth of juvenile Chum Salmon (Farley et al. 2009; Hunt et al. 2011). Since 2006, the Bering Sea has been in a “cool” climate regime, which has been shown to be beneficial for salmon energetics and food availability in the Arctic (Andrews et al. 2009; Coyle et al. 2011; Hunt et al. 2011; Prechtl 2014). Characteristic of this current regime are early sea ice retreat in the Bering Sea which creates ice-associated phytoplankton blooms that produce large, lipid-rich copepods in the pelagic environment (Hunt et al. 2011; Brown and Arrigo 2013; Prechtl 2014).

It has been hypothesized that some higher Arctic regions, including the Chukchi Sea, may be resistant to climate change (Sigler et al. 2011) and that some sub-Arctic pelagic fish species are expected to move northward with a warming climate and less extant sea ice, including juvenile Pacific salmon species (Sigler et al. 2011). Changes in the extent of sea ice and climate variability have the potential to alter key life-history stages, including entry to the marine environment and early marine growth, which have implications for abundance and status of Chum Salmon stocks. Growth rates in juvenile salmon will likely respond to climate change due to altered metabolic rates and shifts in prey abundance, composition, and distribution (Crozier et al. 2008; Moss et al. 2009).

Recent research efforts have examined Arctic ecosystems and the impacts that climate change may have on these diverse and productive areas (Sigler et al. 2011; Nielsen et al. 2013), which has created an interest in gaining knowledge of life-history patterns of Arctic fishes. This project is part of the larger Arctic Ecosystem Integrated Survey (Arctic Eis), which began in summer 2012 and continued through fall 2013. This survey was funded by the Coastal Impact Assistance Program (CIAP), Bureau of Ocean Energy Management (BOEM), and the National Oceanic and Atmospheric Administration (NOAA) with the following goals:

1. Collect baseline fisheries and oceanographic data to enable resource managers to better predict effects of climate and human impacts on ocean productivity and on the ecology of marine and anadromous fish species within the northeastern Bering Sea and Chukchi Sea;
2. Assess the distribution, relative abundance, diet, energy density, size, and potential predators of juvenile salmon, other commercial fish, and forage fish within the northeastern Bering Sea and Chukchi Sea;

3. Evaluate the effect of climate change on the health and status of pelagic fishes within the northeastern Bering Sea and Chukchi Sea (NOAA 2012).

Collaboration between NOAA, the Alaska Department of Fish and Game, and the University of Alaska Fairbanks has allowed this survey to comprehensively examine the Chukchi Sea region for the first time. Information gained during this project will be used to better understand marine conditions in the Arctic with respect to climate change.

Although most Chum Salmon are harvested from the Bering Sea and southeastern Alaska, there is little information on early marine life-history stages as far north as the Chukchi Sea. The utilization and dependency of Chum Salmon as a resource in western Alaska makes this critical period in their life history necessary when understanding the health and status of stocks in these regions. The prevalence of climate change occurring in the Arctic and sub-Arctic is even more reason to understand factors that affect the overall production of Chum Salmon. This thesis will describe the timing of marine entry and growth rates of juvenile Chum Salmon in Alaskan waters of the northern Bering and Chukchi Seas, which are important rearing habitats for western Alaska populations. This study focus will provide baseline data on Chum Salmon marine-entry timing and growth, and provide insight into their early marine life-history characteristics which can be used for comparisons with future studies.



## **Chapter 1: Marine-entry timing and growth rates of juvenile Chum Salmon in Alaskan waters of the northern Bering and Chukchi Seas<sup>1</sup>**

### **Introduction**

Pacific salmon *Oncorhynchus* spp. in the north Pacific Ocean are affected by changing oceanographic conditions (e.g., sea ice coverage, temperature regimes, and changing salinities) due to current warming trends in the Arctic (Sigler et al. 2011; Nielsen et al. 2013). Climate-change predictions include warmer temperatures at higher latitudes, hydrographic changes for salmon-bearing streams, and rising sea surface temperatures (SSTs; Crozier et al. 2008). Future changes in climate may cause fish populations to exhibit shifts in response to ecological changes (Walther et al. 2002; Reist et al. 2006), which includes range extensions, altered timing of spawning runs, and the ecology and dynamics of life-history stages (Walther et al. 2002; Reist et al. 2006; Nielsen et al. 2013). These changes have implications on distribution and abundance of Pacific salmon species in the northern Bering and Chukchi Seas.

Chum Salmon *Oncorhynchus keta* are the second most abundant (Irvine and Fukuwaka 2011) and most widely distributed and Pacific salmon species in North America, ranging from northern California to the Mackenzie River drainage in the Canadian Arctic (Salo 1991; Stephenson 2005). While common in Alaskan waters of the Bering and Chukchi seas, the Gulf of Alaska, and river systems throughout most of Alaska, spawning populations of Chum Salmon can be found in the tributaries of the North Slope and along the Arctic Ocean and Beaufort Sea coasts (ADF&G 2015a). Throughout Alaska, Chum Salmon are an important commercial,

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subsistence, and recreational resource. Commercial harvest in Alaska in 2012 was over 63,000 metric tons and was valued at over \$93 million USD, making Chum Salmon one of the most valuable salmon species in the state (NOAA 2015). In the Arctic-Yukon-Kuskokwim (AYK) area which drains into the Bering, Chukchi, and Beaufort seas, commercial harvests of Chum Salmon totaled over one million fish in 2012 (Eggers et al. 2013). In these western and northwestern Alaska drainages, subsistence harvest of Chum Salmon is commonly the primary salmon resource available (Wolfe and Spaeder 2009). Catches of Chum Salmon for subsistence use often exceed commercial harvests, with average catches in the Yukon River drainage well over 100,000 fish per year since the 1990's (both summer and fall runs) and over 60,000 fish per year since 2000 in the Kuskokwim River drainage (Brown and Jallen 2012; Ikuta 2012; Eggers et al. 2013; ADF&G 2015b).

Understanding the early marine stages of juvenile Pacific salmon life history is critical to our understanding of not only their basic biology, but also how climate change may affect survival and recruitment. Juvenile Chum Salmon have a brief freshwater residence time and migrate to the ocean soon after emergence from their redd (Holtby et al. 1989; Salo 1991; Quinn 2005). The timing of outmigration is important for juveniles so that they reach the marine environment when food resources are available for optimal growth and survival (Mueter et al. 2005; Quinn 2005; Moss et al. 2009a). A warmer Arctic will affect the timing of spring sea ice retreat, which could affect nearshore productivity and food availability for juvenile salmon (Moss et al. 2009b; Sigler et al. 2011). Therefore, it is important to understand the marine entry timing of juvenile Chum Salmon in relation to climate change and to assess how these changes may impact early life-history stages of stocks of this species in the northern Bering and Chukchi seas.

The first summer spent in the ocean following freshwater outmigration is a critical period for Pacific salmon growth. It has been hypothesized that juvenile salmon that do not reach a critical size during their first summer at sea will most likely not survive the harsh metabolic demands of winter (Holtby et al. 1990; Beamish and Mahnken 2001; Farley et al. 2007; Farley et al. 2009). As a result, year-class strength has been shown to be directly related to growth during the first marine year (Sogard 1997; Beamish et al. 2004). Juvenile salmon must grow rapidly to survive in this environment because of high size-dependent mortality (Healey 1982; Farley et al. 2007). Further, larger individuals are more likely to survive periods of starvation due to higher energy reserves than smaller fish, typically greater tolerance to environmental variability, and are less vulnerable to predation (Sogard 1997; Beamish et al. 2004). Growth rates of juvenile salmon have the potential to respond to climate change because of altered metabolic rates and shifts in prey availability, composition, and distribution (Farley and Moss 2009; Moss et al. 2009c).

Otolith analysis is a valuable tool for estimating age and growth due to the insoluble nature of otoliths and their ability to record physiochemical environments occupied by an individual fish (Campana and Neilson 1985; Campana 1999; Campana and Thorrold 2001). This attribute is due to the composition of otoliths (primarily calcium carbonate) and the incorporation of trace elements in proportion to ambient ratios of the surrounding waters in which a fish resides (Bath et al. 2000; Campana 1999; Arai and Hirata 2006). The use of otolith microchemistry, in particular otolith strontium (Sr) concentrations, is a useful method for determining changes in salinity histories of diadromous fishes, including juvenile Pacific salmon (Arai and Miyazaki 2002; Zimmerman 2005; Walther and Limburg 2012). Marine environments have higher ambient Sr concentrations than freshwater systems, which allows timing and movements from fresh to marine waters to be detected in fish otoliths (Zimmerman 2005; Arai and Hirata 2006). Chum

Salmon, like most fishes, have been shown to deposit growth increments on otoliths on a daily basis (Saito et al. 2007), which have been used in studies to reconstruct juvenile Chum salmon marine entry timing (Murphy et al. 2009). By knowing the timing of marine entry on a regional scale, as well as being able to make annual comparisons, variations in juvenile Chum Salmon migration timing due to changing climatic conditions should be detectable in the future.

The effects of climate change on salmon life-history characteristics are not fully understood. However, Crozier et al. (2008) has suggested that the environmental diversity and behaviors exhibited by Pacific salmon allows for the alteration of life-history responses in the face of climate change, including juvenile migration timing and early marine growth rates. As a result, there is a clear need to understand the early marine period of Pacific salmon life history in the northern Bering and Chukchi Seas. Both regions are known to be important for the feeding, growth, and subsequent survival of juvenile Chum Salmon in western Alaska (Farley et al. 2009; Moss et al. 2009c; Sigler et al 2011). However, the Chukchi Sea remains a data-poor region which has been minimally studied with respect to juvenile salmon ecology. By understanding the full range of juvenile Chum Salmon early life-history characteristics and growth information at a regional scale, managers will be better equipped for making predictions on climate change effects on the future distributions and dynamics of fish species such as Chum Salmon in important Alaskan rearing areas such as the northern Bering and Chukchi seas. The objectives of this study were: 1) to compare the timing of marine entry of juvenile Chum Salmon in the northern Bering and Chukchi seas; and 2) compare early marine growth rates of juvenile Chum Salmon using otolith aging and microchemistry techniques. This research provides a baseline on the status of juvenile Chum Salmon in the northern Bering and Chukchi seas, and may act as a benchmark for future comparisons that result from a changing Arctic climate.

## Methods

### *Fish collection*

Juvenile Chum Salmon were collected during the U.S. Bering-Aleutian Salmon International Survey (BASIS) in August-September 2007 onboard the National Oceanic and Atmospheric Administration (NOAA) R/V *Oscar Dyson*. In August-September 2012 and 2013, trawls were conducted by the F/V *Bristol Explorer* during the Arctic Ecosystem Integrated Survey (Arctic Eis; Figures 1 and 2). A Cantrawl model 400/601 (Cantrawl Pacific Limited, Richmond, British Columbia) midwater hexagonal mesh trawl with a 12-mm mesh codend liner was used to sample to a depth of 20 m, was 198 m long, had approximately a 50-m horizontal opening, and 120-m headrope. Trawl dimensions can be variable with conditions and vessel configurations over time. Each tow at a station (which were spaced at 55-km intervals) lasted 30 minutes in duration at target speeds between 7.4 and 9.3 km per hour (km/hr) along latitudinal and longitudinal lines in the Chukchi Sea (CS; 66° N-70° N) and northern Bering Sea (NBS; 60° N-65.5° N) east of -170° W longitude (see Figure 2 in Moss et al. 2009c). Trawls were only conducted during daylight hours.

During the three trawl surveys, fish collected during each haul were sorted onboard by species and subsamples of each species were measured for fork length (FL) to the nearest 1 mm and wet weight to the nearest 1 g using motion compensated electronic scales. If less than 50 juvenile Chum Salmon were caught at a station, all fish were kept for biological sampling, which included otolith extraction. However, if more than 50 juvenile Chum Salmon were caught in a trawl haul, a random subsample of 50 fish across all measured sizes were selected for biological sampling. Retained heads or whole fish were frozen at -20°C onboard, labeled with collection information (e.g., station number, sampling date, and length/weight barcode), and transported to

Auke Bay Laboratory in Juneau, Alaska, for subsequent otolith removal. Samples from the NBS in 2013 were not included in these analyses due to a flooding event onboard the F/V Bristol Explorer, which resulted in the loss of all samples collected from this region.

To evaluate marine-entry timing and growth rates of juvenile Chum Salmon, a subsampling approach was used to select otolith samples from the CS and NBS. To subsample from NBS in 2007, the CS in 2007, and the NBS in 2012, collected fish were organized into 20-mm FL-frequency bins (Table 1). Samples from the NBS in 2007 were prepared and analyzed at Auke Bay Laboratories in Juneau, Alaska (Murphy et al. 2009). For these samples, an even proportion of samples from each FL-frequency bin, with the exception of the largest bin which had only three samples, were selected for otolith analyses (Table 1). To subsample the CS in 2007 and the NBS in 2012, all samples were used from FL-frequency bins with fewer than 10 samples. If a station had less than five juvenile Chum Salmon samples collected from it, all were used from that station for analyses. For all other FL-frequency bins and stations, samples were chosen at random, alternating among bins and chosen from all stations, until total sample sizes reached between 100 and 110 fish for consistency in sample sizes across regions and years (Table 1). In the cases of the CS in 2012 and 2013, all samples were used for analyses due to low catches in this region.

To remove otoliths, a dorso-ventral cut from the top of the head through the preopercle was made just anterior to the fleshy margin atop the head to expose the brain and semicircular canals (Secor et al. 1991). Both sagittal otoliths were removed, gently wiped of blood and the otolithic membrane, and rinsed in deionized water. Once dry, otoliths were placed in sterile 1.5-ml centrifuge tubes (one pair of otoliths per tube), and the tubes were marked with collection information.

### *Otolith preparation*

The left sagittal otoliths of juvenile Chum Salmon were mounted sulcus-side down on individual microscope slides with Crystalbond<sup>TM</sup> thermosetting plastic resin mounting adhesive (Structure Probe, Inc., West Chester, Pennsylvania). Otolith pairs from ten fish were compared in rostrum-post rostrum length and dorso-ventral width, and did not differ by more than the distance of a single day of fish growth (i.e. deposition of one daily increment). As a result, it was assumed that each otolith of a pair from the same fish contained identical growth histories. If the left otolith was found to be vateritic (a calcium carbonate polymorph which does not allow daily rings to be seen; Falini et al. 2005) or broken, the right otolith was used in its place. Otoliths were thin sectioned along the sagittal plane using a Histologic Precision Grinding Fixture (Buehler Ltd., Lake Bluff, Illinois) and hand-ground on wet 5- $\mu$ m lapping film (Precision Surfaces International, Houston, Texas) until daily growth increments were visible. Just prior to reaching the core, the microscope slide was reheated using a hot plate and the otolith was turned over on the slide (Neilson and Geen 1981; Courtney et al. 2000). The opposite side of the otolith was then polished until the core and daily growth increments could be clearly observed using a Leica compound microscope (Leica Microsystems, Wetzlar, Germany) with transmitted light at 100x magnification. Polishing was halted before over-polishing, which would erase daily growth history.

Preparation of otoliths from the NBS in 2007 differed slightly from the other four sampling region/year combinations. These samples were prepared at the NOAA facilities in Juneau, Alaska, and polished by hand on a LaboPol-21 polishing machine (Struers, Inc., Cleveland Ohio) using 1200 and 4000 grit wet-dry sandpaper under flowing water (Murphy et al. 2009). Batch slides of otoliths were created, leveled using a digital micrometer to determine a

uniform thickness, and then briefly polished with 8000 grit micro-mesh polishing cloth (Murphy et al. 2009). All other aspects of preparation were identical to procedures followed for 2012 and 2013 samples.

### *ICP-MS*

Otolith chemical analyses were completed using an Agilent 7500ce inductively-coupled plasma mass spectrometer (ICP-MS; Agilent Technologies, Inc. Santa Clara, California) fitted with a cs lens stack and coupled with a New Wave UP213 laser ablation system (New Wave Research, Fremont, California) at the University of Alaska Fairbanks (UAF) Advanced Instrumentation Laboratory. Data were collected on elemental masses, which included  $\text{Mg}^{24}$ ,  $\text{Zn}^{66}$ ,  $\text{Ba}^{138}$ ,  $\text{Mn}^{55}$ ,  $\text{Ca}^{42}$ ,  $\text{Ca}^{43}$ ,  $\text{Sr}^{86}$ , and  $\text{Sr}^{88}$ . The ICP-MS signal was optimized each day using masses 9 (Be), 139 (La), and 238 (Ur) to maximize signal response across the mass range of the mass spectrometer. Parameters on the ICP-MS were set to a radio-frequency (RF) power of approximately 1,200 W and an RF matching of approximately 1.62 V. Laser parameters were set to a scan speed of  $10 \mu\text{m} \cdot \text{s}^{-1}$ , a spot size of  $25 \mu\text{m}$ , pulse frequency of 10 Hz, laser power of 80%, and focus depth of  $5 \mu\text{m}$ . All of these parameters are known in this system to optimize performance of the instruments across the entire mass range for otolith samples (K. Spaleta, UAF, personal communication). All ablations occurred in a helium atmosphere, and a NIST 610 ( $\text{Ca}^{43}$ ) standard reference material was used as a calibration standard. Raw data were processed and calibrated with the Iolite software package (Melbourne Iolite Group, Melbourne, Australia; Paton et al. 2011) using the method described in Longerich et al. (1996). Molar weights of Ca ( $40,078 \mu\text{g} \cdot \text{mol}^{-1}$  ( $\mu\text{g} \cdot \text{mol}^{-1}$ )), Sr ( $87,620 \mu\text{g} \cdot \text{mol}^{-1}$ ), and Mn ( $57,938 \mu\text{g} \cdot \text{mol}^{-1}$ ) were used to convert elemental concentrations to elemental molar ratios as:

$$\text{An:Ca} = C_{\text{AN}} * (W_{\text{CA}} / W_{\text{AN}}) * (1,000 / C_{\text{IS}}),$$

where  $C_{\text{AN}}$  was the concentration in ppm of a given element in the sample (Sr, Mn, etc.),  $W_{\text{AN}}$  was the molar weight of analyte,  $W_{\text{CA}}$  was the molar weight of calcium, and  $C_{\text{IS}}$  was the concentration in ppm of internal NIST 610 standard ( $383,000 \mu\text{g} \cdot \text{mol}^{-1}$ ).

Ablations took place on a transverse cross-section from the ventral to the dorsal side of the otolith passing through the core, or primordia. Molar ratios of strontium to calcium (Sr:Ca) across the edge-to-edge transect were used to identify the transition from freshwater to the marine environment due to higher relative ambient concentrations of strontium in marine environments (Zimmerman 2005; Arai and Hirata 2006). A sharp increase in otolith strontium concentration along the molar ratio transect gave a chemical reference point for marine entry (Figure 3). Although there is variation in the magnitude of Sr:Ca ratios among different aquatic systems (Campana 1999; Zimmerman 2005; Arai and Hirata 2006), the use of these ratios gives sufficient discrimination to distinguish between freshwater, brackish water, and seawater for the different life-history stages of diadromous fishes (Arai and Miyazaki 2002; Zimmerman 2005; Walther and Limburg 2012). For the purposes of this study, the pattern of increasing Sr:Ca ratios in the otoliths were adequate to describe the movement of Chum Salmon smolts from freshwater to seawater, as well as determine visually the location of the check of marine entry (Saito et al. 2007).

The chemical cores of otoliths were identified by a peak in the molar ratio of manganese to calcium (Mn:Ca; Figure 3). High concentrations of manganese in otoliths cores are seen in fishes whose eggs incubate in gravel substrates as well as species that do not have a gravel incubation period, suggesting that a period of active manganese uptake takes place during embryological development in fishes regardless of reproductive strategies (Brophy et al. 2004).



To identify a marine-entry point on the otolith, the chemical reference points from Sr:Ca and Mn:Ca molar ratio plots (Figure 3) were overlain onto the sectioned otolith images (Figure 4). These were inspected to identify the visual patterns that corresponded to increases in Sr:Ca molar ratios, i.e., marine-entry checks. These checks could be detected as a lightened zone of daily growth increments (Figure 4).

Otolith microchemistry has been used to detect movement of juvenile Chum Salmon from freshwater to estuarine and marine environments (Arai and Miyazaki 2002; Arai and Hirata 2006; Murphy et al. 2009). For the purposes of this study, otolith chemistry using ICP-MS was used as a validation for the marine-entry point on the otolith. A subsample of 20-22 otoliths (82 total) across the entire FL range from each region and year combination were used for validation purposes to establish the accuracy and precision of estimating ocean entry via growth checks (Table 2). Samples from 2007 NBS were the exception to this subsampling approach because Murphy et al. (2009) used all 112 prepared otoliths for chemical analysis using the ICP-MS (Table 2).

For the remainder and majority (82%) of the samples, entry checks were determined using visual estimation. With previous knowledge of the chemical reference point (Murphy et al. 2009) and confidence in the visual check of marine entry, it was decided that using a subsample for chemical analysis for both cost- and time-efficiency would be a reliable method for entry-check validation. Visual checks of physiological responses to the environment of the fish, (i.e. ring patterns) were used to denote the timing of marine entry (Marshall and Parker 1982; Murphy et al. 2009). Non-periodic check formation, or changes in increment width and appearance of daily growth rings, has been shown to be caused by times of physiological stress (e.g., hatching and smoltification; Neilson and Geen 1982; Neilson et al. 1985; Campana and

Neilson 1985) and may be used as a benchmark for marine-entry timing (Saito et al. 2007; Murphy et al. 2009). Determination of the marine entry of juvenile Chum Salmon was readily visible in most processed otoliths. Chemical analysis allowed for consistent visual identification of marine-entry points on otolith transects.

Growth increments were assumed to be deposited daily for this study based on the validation of daily increment formation for juvenile Chum Salmon by Saito et al. (2007). Daily increments were counted back from the otolith edge to the beginning of the sharp transition from low to high strontium concentrations (the smolt check) by two readers using Image Pro Plus software (Version 7.0, Media Cybernetics Inc., Rockville, Maryland). If there was not agreement between readers, a concert read was conducted by both individuals and an agreement was reached. The date of marine entry for each fish was calculated by subtracting the total number of daily increments from the date of fish capture, which included the transition zone (beginning of the increase in strontium). Between 51- 63% of prepared otoliths had a smolt check but did not yield clear daily growth increments that were countable. For those fish, the average number of increments found in the transition zone for readable otoliths for juvenile Chum Salmon captured in that region/year were added to marine age of non-readable otoliths (generally 12 or 13 increments) which gave a total marine age of fish in days (Murphy et al. 2009). This time period concurs with previous studies of Chum Salmon otolith analyses and smolt residency in river deltas and estuaries in the NBS region (Martin et al. 1987; Murphy et al. 2009). Sub-daily growth increments were occasionally present in otolith samples and were accounted for by adjusting the focal depth of the microscope and counting daily growth increments on multiple axes of the otolith until a decision was made to include the increment as a true daily growth increment or consider it as a sub-daily growth increment (Murphy et al. 2009). These sub-daily

growth increments were generally poorly defined and could be distinguished from a true daily growth increment with validation (Marshall and Parker 1982; Neilson 1992; Murphy et al. 2009).

### *Data analysis*

#### *Marine-entry timing*

Dates of marine entry for all samples were determined by subtracting counts of daily growth increments from the capture date of each fish. Mean marine-entry dates of juvenile Chum Salmon between the CS and NBS regions and among 2007, 2012, and 2013 were compared using a one-way Analysis of Variance (ANOVA). Residual plots were used to test assumptions of normality and equal variance, and a Tukey's HSD (honest significant difference) multiple comparisons test was used to compare mean entry dates.

#### *Juvenile growth*

Growth rates of juvenile Chum Salmon were compared between the CS and NBS regions and among 2007, 2012, and 2013. Marine age of juvenile Chum Salmon was used as the explanatory variable regressed against FL to detect differences in length-at-age growth among regions and years. Marine age was regressed exponentially versus weight (g) to determine the overall growth relationship for each region (i.e., CS and NBS) and year (i.e., 2007, 2012, and 2013). Exponential growth was modeled as:

$$y_i = \alpha e^{\beta x_i},$$

where  $y_i$  was the wet fish weight in g,  $x_i$  was the age in days of the  $i$ th fish, parameter  $\alpha$  was the intercept, and parameter  $\beta$  was the slope, or relative growth rate (Santos et al. 2002). Growth models were then natural log-transformed to fit a linear regression of the form:

$$\ln(y_i) = \ln(\alpha) + \beta x_i + \varepsilon.$$

The parameter  $\beta$  in both equations can be used as an estimate of growth in weight per day (wt/d), which was converted to percent body weight per day (%/d) when multiplied by 100 (Ricker 1979; Murphy et al. 2009). The slope coefficients found using these regressions were a proxy for growth rates that represent weight-at-age growth of juvenile Chum Salmon and were used to compare differences between the two regions and among the three years. Analysis of Covariance (ANCOVA) was used to determine if differences existed among year and region slope coefficients, and residual plots were used to test assumptions of normality and equal variance. All statistical analyses were conducted using the computing environment R and associated packages, version 2.14 (R Core Team 2015), and were considered significant at  $\alpha = 0.05$ .

## **Results**

During the 2007 BASIS survey, juvenile Chum Salmon were caught at 20 stations in the CS and 36 stations in the NBS (see Figure 2 in Moss et al. 2009c). Only three stations yielded juvenile Chum Salmon in the CS in 2012 and 2013, whereas 16 stations yielded juvenile Chum Salmon in the NBS in 2012. The 2007 survey collected larger numbers of juvenile Chum Salmon from stations in the CS, totaling 292 fish from both near and offshore stations. All otoliths collected from the 2012 and 2013 CS survey samples, aside from broken or unusable samples, were used for aging analyses due to low catches at a small number of stations (Table 1; Figures 1 and 2). Forty-two juvenile Chum Salmon out of 98 individuals analyzed from the CS in 2012 and 52 fish out of 93 individuals from the CS in 2013 were from the two southernmost, nearshore stations (Figures 1 and 2). The remainder of the samples from the CS in 2012 and 2013 were from one nearshore station at 69° N and 68° N, respectively. In contrast, samples from the NBS in both 2007 and 2012 were collected from both nearshore and offshore stations (see

Figure 2 in Moss et al. 2009c; Figure 1). In 2012, catches of juvenile Chum Salmon in the NBS were greatest between 60° N and 62° N in nearshore stations (Figure 1). Smaller catches per station were observed in the NBS in 2013, but juvenile Chum Salmon were caught at more offshore stations than in 2012 (Figure 2).

Juvenile Chum Salmon collected from the CS in 2007 ranged from 135 to 220 mm in FL and 20 to 126 g in weight (Table 2). Northern Bering Sea juvenile Chum Salmon collected that year had similar FL (141 to 252 mm) and weights (30 to 187 g), but had higher maximum FL and weights (Table 2). In 2012 and 2013, juvenile Chum Salmon collected from the CS ranged from 90 to 160 mm in FL and 6 to 40 g in weight, whereas juveniles from the NBS ranged from 120 to 217 mm in FL and 16 to 104 g in weight in 2012 (Table 2).

#### *Marine-entry timing*

The timing of entry to the marine environment for juvenile Chum Salmon ranged from mid-June to mid-July among regions and years (Table 3). Fish captured earlier in the year (2012/2013 CS) were smaller in FL and had fewer marine increments than fish captured later in the year (CS 2007, NBS 2007, and NBS 2012; Table 3). Smaller fish at the time of capture entered the marine environment later in the growing season than larger individuals, i.e., mean marine otolith increments were fewer for smaller fish (Table 3). Larger fish had more daily marine increments, with differences between the largest and smallest FL individuals in each region/year combination ranging from 12 to 23 increments, or 12 to 23 days (Table 3). The standard deviations of mean entry dates increased with both fish size and sample size in each length bin (Table 3). Mean marine entry dates between each region/year were significantly different ( $F=17.65$ ,  $P < 0.001$ ; Figure 6; Table 4). Juvenile Chum Salmon from the CS in 2007

had a significantly earlier mean entry date than the other region/year combinations, with the exception of juvenile Chum Salmon from the CS in 2013 (Figure 5; Table 4). The mean entry date of juvenile Chum Salmon from the NBS in 2012 was significantly later than all other region/year combinations (Figure 5; Table 4). Juvenile Chum Salmon from the CS in 2007 had the earliest mean entry date (June 26, d 177), and NBS fish had the latest mean entry date (July 1, d 183) over all five region/year combinations.

#### *Juvenile growth rates*

Growth rates of juvenile Chum Salmon in length-at-age and weight-at-age showed similar characteristics across regions and years. Length-at-age did not differ significantly among sampled regions and years ( $F = 1.29$ ,  $P = 0.272$ ; Figure 6). Slope coefficients of linear models of length-at-age showed growth rates of 2.31mm/d, 2.47 mm/d, 2.60 mm/d, 2.82 mm/d, and 2.41 mm/d for CS 2007, CS 2012, CS 2013, NBS 2007, and NBS 2012, respectively, with an overall average of 2.52mm/d (Figure 6). Differences in weight-at-age were detected among regions and years ( $F = 345.2$ ,  $P < 0.001$ ; Figure 7). Exponential growth models of weight-at-age showed that growth rates of juvenile Chum Salmon were 4.18%/d, 5.34%/d, 6.77%/d, 4.96%/d, and 4.88%/d for CS 2007, CS 2012, CS 2013, NBS 2007, and NBS 2012, respectively, with an overall average of 5.23%/d (Figure 7). Only juvenile Chum Salmon weight-at-age growth rates from the CS in 2013 were significantly different from the other region/year combinations ( $F = 8.2$ ,  $P = 0.005$ ; Table 5; Figure 7). Growth rates from all others region/year combinations were not significantly different from each other (Table 5).

## Discussion

Juvenile Chum Salmon marine-entry timing and growth rates were largely similar among the three years and between the two regions sampled in this study. The timing of marine entry by juvenile Chum Salmon occurred consistently between mid-June and mid-July, and fish exhibited similar characteristics in marine-entry timing in both regions. The larger Chum Salmon that were captured in the NBS and CS most likely entered the marine environment earlier in the growing period (i.e., had an earlier timing of marine entry) than smaller individuals at the time of capture. This outcome (i.e., larger body size) was because the earlier outmigrants had a longer time to feed and grow in the marine environment relative to smaller fish which entered marine waters later in the growing season. Growth rate estimates were consistently 4-5% of body weight per day (%/d), with the exception of the CS in summer 2013 which had a higher growth rate (6.8%/d) than the other region/year combinations. These early marine life-history stage attributes of Chum Salmon have the potential to be affected by climate change in these regions of the Alaskan Arctic, as has been suggested by other studies (Crozier et al. 2008; Ruggerone and Nielsen 2009; Irvine and Fukuwaka 2011; Sigler et al. 2011; Prechtl 2014).

### *Marine-entry timing*

Marine-entry timing of juvenile Chum Salmon in this study was consistent between the NBS and CS and among sampling years, which corroborates previous evaluations of marine-entry timing for early life stages of this species. Dates of marine entry in the CS ranged from June 16 in summer 2013 to July 16 in summer 2007, while marine-entry timing in the NBS ranged from June 8 in summer 2007 to July 17 in summer 2012. Merritt and Raymond (1983) observed peak outmigration of juvenile Chum Salmon from the Noatak River, a tributary of

Kotzebue Sound and the CS, to occur from mid to late June in 1981. In summer 1986, Martin et al. (1987) observed that catch per unit effort (CPUE) of outmigrating juvenile Chum Salmon in the Yukon River delta peaked from mid to late June. Nemeth et al. (2006) observed similar outmigration timing for juvenile Chum Salmon in northern Norton Sound, with peaks in CPUE occurring in mid-June and mid-July in 2003 and 2004. In summer 2014, CPUE for juvenile Chum Salmon outmigrating from the Yukon River delta peaked in the final week of May and again in the third week of June (K. Howard, ADF&G, unpublished data). These findings are consistent with known Chum Salmon life-history strategies, where downstream movement of fry occurs directly after river ice break-up in spring and continues through the summer months (Salo 1991; Quinn 2005).

Marine-entry timing dates for juvenile Chum Salmon in this study corresponded with the timing of ice break-up in the spawning tributaries for Chum Salmon (NBS: the Yukon and Kuskokwim rivers, Norton Sound area, and northeastern Russia; CS: the Seward Peninsula, and the Kobuk and Noatak rivers of Kotzebue Sound; Kondzela et al. 2009, 2014). Previous research has shown that ice break-up during spring months is the primary determinant of juvenile salmonid outmigration from freshwater to marine environments (Jutila et al. 2005; Quinn 2005; Prowse et al. 2011; Jensen et al. 2012). River ice break-up occurred in early May 2007, mid-May 2012, and late May 2013 in tributaries of the NBS, whereas break-up in tributaries of the CS took place during the final week of May for all three sampling years (NWS 2015). The longer distance that juvenile Chum Salmon travel downstream in NBS tributaries (up to 3,000 km to the headwaters of the Yukon River; ADF&G 2015a) compared to Kotzebue Sound tributaries (up to 160 km to the headwaters of the Noatak River; Bigler and Burwen 1984), along with more variable river ice break-up dates in NBS tributaries (NWS 2015), are likely to be contributing



factors for the more variable marine-entry timing of Chum Salmon in the NBS. Previous studies have suggested that Chum Salmon stocks with different life-history types (i.e., summer and fall Chum Salmon in the Yukon River) could cause more variability in marine-entry timing in the NBS (Martin et al. 1987; Murphy et al. 2009). Nemeth et al. (2006) showed that juvenile Chum Salmon enter the marine environment as three distinct groups in northern Norton Sound, which could also be a factor in variability of marine-entry timing of juvenile Chum Salmon in the NBS. More information on life-history type and river of origin are needed to tease out differences in marine-entry timing of mixed stocks of Chum Salmon.

There are several environmental determinants of marine-entry timing for juvenile Pacific salmon in Arctic and sub-Arctic regions. Outmigration timing has been shown to be influenced by the synergistic interaction of increasing photoperiod, water temperature, and river discharge during spring months, which corresponds to spring ice retreat and river ice break-up in high latitude rivers (Holtby et al. 1989; McCormick et al. 1998; Antonsson and Gudjonsson 2002; Byrne et al. 2004; Jutila et al. 2005; Reist et al. 2006; Prowse et al. 2011; Jensen et al. 2012). These environmental changes are cues for initiating outmigration and the facilitation of downstream movement to marine environments for juvenile salmonids (McCormick et al. 1998; Quinn 2005; Jensen et al. 2012). Chum Salmon are known to migrate quickly downstream after redd emergence at a rate similar to ambient water velocity (Salo 1991; Quinn 2005). As a result, marine entry of juvenile Chum Salmon is coupled with the timing of these environmental cues during spring as day length increases, discharge increases with ice and snow melt, and water warms into summer. It has been suggested that the timing of smolt outmigration may be an adaptation to environmental conditions at varying latitudes and systems (Holtby et al. 1989; Jutila et al. 2005; Jensen et al. 2012). Consequently, the consistency in marine-entry timing for

juvenile Chum Salmon in this study suggests that the timing of marine entry in the NBS and CS systems may be an adaptation to allow for the greatest utilization of abiotic and biotic resources during the short growing season that occurs at high latitudes (Holtby et al. 1989; McCormick et al. 1998; Tomaro et al. 2012; Miller et al. 2014; Satterthwaite et al. 2014).

Climate change in the Arctic could likely influence the timing of marine entry for juvenile Chum Salmon through warming water temperatures and changes in ice break-up timing in spawning tributaries. As a result, there are a variety of outcomes that may result from a warming climate in the NBS and CS. When early life stages are exposed to less than optimal environmental conditions during critical periods (i.e., first feeding), mortality can be high (Cushing 1990). Previous studies have shown that in years when the timing of juvenile salmon marine entry concurs with the availability of lipid-rich copepods and other favorable abiotic conditions (i.e., temperature), fish survival is higher (Cross et al. 2008; Tomaro et al. 2012; Woodson et al. 2013; Miller et al. 2014). Therefore, earlier river ice break-up in spring that is to be expected to result from warming temperatures in the Arctic could lead to earlier outmigration timing of juvenile Chum Salmon into nearshore marine environments. However, a shift towards earlier outmigration timing could lead to a mismatch in the arrival of juvenile fish to the marine environment relative to prey availability if smolts do not arrive at a time that allows for optimum feeding and growth conditions (Reist et al. 2006; Cross et al. 2008; Crozier et al. 2008; Prowse et al. 2011; Nielsen et al. 2013; Satterthwaite et al. 2014). This scenario would have negative impacts on growth and survival during the first marine summer. Further, altered timing of ice retreat in the Bering and/or Chukchi seas could cause plankton blooms to occur at different times in spring, which has implications for the assemblage, quality, and quantity of available zooplankton prey available (Coyle et al. 2011; Hunt et al. 2011). As a result, alterations to

temperature and changes in ice break-up and river discharge that will likely accompany a warming climate will not only affect the timing of key life-history stages, but also likely the productivity of Chum Salmon in Arctic waters (Crozier et al. 2008; Sigler et al. 2011; Grebmeier 2012). Continual monitoring of environmental conditions in both freshwater and marine environments is needed to assess future scenarios in relation to impacts on juvenile Chum Salmon and other fish species with respect to climate change (Sigler et al. 2011).

### *Juvenile growth rates*

Juvenile Chum Salmon growth rates in this study were largely consistent between regions and among years, and are in agreement with previous growth rate estimates for juveniles of this species. Growth rates in the CS ranged from 4.2%/d in summer 2007 to 6.8%/d in summer 2013, with the latter estimate being significantly higher than all other region/year combinations. For the NBS, the range of growth rates ranged from 4.9%/d in summer 2012 to 5%/d in summer 2007. Similarly, Murphy et al. (2009) estimated growth rates of juvenile Chum Salmon that were collected from the southern and northern Bering seas in summer 2007 to be 5.1%/d. Salo (1991) reported that growth rates of juvenile Chum Salmon in nearshore areas of British Columbia averaged 4 to 6%/d, with an upper limit of 6.7%/d. Relatively high growth rates have also been observed for juvenile Chum Salmon in Puget Sound, Washington (5.7 to 8.6%/d; Salo et al. 1980; Duffy et al. 2005). Average growth rates of thermally marked hatchery Chum Salmon in southeast Alaska have also been estimated to range between 3 and 6%/d (J. Murphy, NOAA, personal communication). These growth rate estimates, although not widely variable, suggest that differences in environmental conditions throughout Alaska might differentially affect growth rates of juvenile Chum Salmon in different regions.

Observed differences in the daily age at which juvenile Chum Salmon attained the same weight between the NBS and the CS (i.e., fish of the same weight differed by 20 or more marine increments between these regions) suggests that there may be differences in the timing of smolt check formation. There appears to be a time lag between check formation on an otolith and when Sr:Ca ratios are observed to increase following marine entry on that same otolith. The lower observed weight at a given daily age for juvenile Chum Salmon in the NBS could be due to differences in environmental conditions between regions and, in turn, how these differences may affect the timing of the smolt check deposition (Campana 1999), specifically differences in estuarine environments. Kotzebue Sound, the major embayment into which several northwestern Alaskan tributaries flow, is a more typical estuary that grades from freshwater to saltwater toward the outlet at the Chukchi Sea (Merritt and Raymond 1983; Smith 2013). Conversely, the Yukon River delta is a large, freshwater-dominated estuary near the river mouth and is highly variable in salinity between the many different locations in the delta where juvenile Chum Salmon inhabit, e.g., distributaries and adjacent tidal channels, extensive mud flats, and outer delta platform (Martin et al. 1987; Murphy et al. 2009). These conditions make for somewhat harsh rearing environments for juvenile Chum Salmon, and Martin et al. (1987) suggested that Yukon River delta habitats serve as staging areas for juveniles before they quickly move offshore, generally at a smaller size than other, more typical, estuarine environments. These contrasting conditions may be a contributing factor for the later smolt check deposition on juvenile NBS Chum Salmon otoliths, and a reason for their lower weight at a given age than juveniles in the CS. When estimated smolt checks were removed from daily age estimates and the subsequent growth models, no differences in growth rate estimates were found, suggesting that the observed differences were likely due to variances in the period of smoltification and/or

timing of smolt check formation that occurs between regions and not due to error in the estimated location of smolt checks or daily age.

There are a number of environmental factors that influence growth rates during the early marine life history for juvenile Pacific salmon. Juvenile salmon must achieve a minimum body size and secure sufficient energy reserves prior to their first winter as well as avoid predation during their first marine summer (Beamish and Mahnken 2001; Duffy et al. 2005; Moss et al. 2005; Farley et al. 2007). The growth rates observed in the current study indicate that juvenile Chum Salmon have a high capacity for growth in the marine environment during their first few months at sea in both the NBS and CS. Although the range of juvenile Chum Salmon growth rates estimated in this study are comparable to other studies on early marine growth for this species, variable environmental conditions among sampling years, such as temperature, food availability, and photoperiod may have contributed to the observed differences in growth rates.

Warmer water temperatures increase fish metabolic rate and, if thermal maxima have not been reached and food availability is sufficient, fish will grow at faster rates (Brett et al. 1969; Clarke and Johnston 1999). During the current study, mean SST was 1°C warmer during summers 2007 and 2013 than in summer 2012 (L. Eisner, NOAA, unpublished data). The relatively high growth rate of juvenile Chum Salmon from the CS in 2013 could be due to the warmer SSTs coupled with increased feeding opportunities and greater primary/secondary productivity from the longer photoperiod at this higher latitude. Moss et al. (2009a) suggested that the higher growth rates of juvenile Chum Salmon that were observed in the CS than the NBS in 2007 were due to these same mechanisms. Although SSTs were relatively warm in summers 2007 and 2013 for both regions, the relatively lower growth rate exhibited by juvenile Chum Salmon in the CS in summer 2007 (4.2%/d) is most likely a result of sampling dates that

occurred one month later than in 2012/2013. Growth rates typically decline as fish grow larger and older, and the later sampling dates in the CS in 2007 could be a contributing factor for the lower observed growth rates in that region/year combination (Brett 1979).

The quality and quantity of prey resources available for juvenile Chum Salmon, as well as the amount of lipid stores that can be derived from those food sources, is important for growth during the early marine period. The significantly higher weight-at-age growth relationship in the CS in summer 2013 and lack of differences in length-at-age relationships between all region/year combinations suggests that length may not be as important as weight when it comes to energy storage to survive the winter. These results are consistent with the findings of Andrews et al. (2009) in which an uncoupling between length and total energy content was observed for eastern Bering Sea juvenile Pink Salmon *Oncorhynchus gorbuscha*. Although body weight is not necessarily indicative of accumulated caloric content or stored energy reserves, juvenile salmon have been shown to exhibit higher total energy content and lipid stores at cooler thermal regimes, which is consistent with the thermal regime in the Bering and Chukchi seas since 2006 (Andrews et al. 2009; Moss et al. 2009b; Prechtel 2014). This current thermal regime supports energetically dense prey that are beneficial for juvenile salmon growth, which may provide one explanation for the consistently higher growth rates observed in both regions of the current study (Farley et al. 2009; Hunt et al. 2011). The higher growth rate observed in the CS in summer 2013 suggest that conditions were more energetically favorable for growth and that prey quality may be higher in the CS than the NBS, perhaps due to the shallower shelf habitat, high primary productivity, and longer day lengths/photoperiod (Grebmeier et al. 2006a; Moss et al. 2009c; Zador 2013).

Previous research has demonstrated that greater feeding opportunities and primary/secondary production due to increased photoperiod at higher latitudes are important for

early life stages of juvenile salmonids in the Arctic (Moss et al. 2009c; Murphy et al. 2009; Jensen et al. 2012). The difference in latitude between the NBS and CS regions (1°N) results in a difference of two hours of sunlight during summer months (UNL 2015). At the highest latitude in the CS (70°N) relative to the lowest latitude in NBS (60°N), maximum sunlight differences at the summer solstice (June 21) provides 5.5 more hours of daylight for the CS. Further, 24 hours of sunlight is available at the higher latitudes of the CS from May through July (UNL 2015). Longer photoperiod coupled with higher SSTs at high latitudes due to climate change have been shown to alter conditions in a manner to make them more conducive to juvenile salmon growth (Farley et al. 2009; Farley and Moss 2009; Moss et al. 2009c; Ruggerone et al. 2010). In addition to the positive effect of day length on growth in fishes (Brett 1979), the increase in daylight for the CS could be a factor influencing phytoplankton production and, therefore zooplankton and fish production, that juvenile Chum Salmon feed on during their first marine summer (Moss et al. 2009c).

The extent of spring ice coverage and the timing of spring ice retreat in the Bering Sea have effects on algal and zooplankton blooms, which impact bottom-up food availability and growth of juvenile Chum Salmon (Farley et al. 2009; Hunt et al. 2011). Ice retreat in the NBS is characterized as being relatively late, which causes an early phytoplankton bloom on the ice edge in cold water (Brown and Arrigo 2013). This phytoplankton bloom produces high abundances of large, lipid-rich copepods, thereby providing more energy for pelagic consumers such as juvenile salmon (Hunt and Stabeno 2002; Grebmeier et al. 2006a; Hunt et al. 2011; Brown and Arrigo 2013). As sea ice melts in spring, nutrient-rich waters from the Bering Sea flow north through the Bering Strait into the CS where oceanographic conditions and zooplankton assemblages are similar to those in the NBS (Grebmeier et al. 2006b; Sigler et al. 2011). However, additional diet

and energetic studies are necessary to untangle the current energetic status and dynamics for these populations of juvenile Chum Salmon and how they might be affected by climate change.

Growth rates for juvenile salmon in the NBS and CS may respond to climate change due to altered metabolic rates and timing of important life-history periods relative to changes in prey abundance, composition, and distribution (Reist et al. 2006; Crozier et al. 2008; Nielsen et al. 2013). Higher growth rates of juvenile Chum Salmon in the NBS and CS would be expected to yield higher survival through the first winter period, with positive implications for adult fish returns (Beamish et al. 2004; Moss et al. 2005). Although warmer SSTs might benefit growth when prey quality is high, bottom-up regulation of nutrients and prey availability for juvenile salmon will likely be affected by changes in sea ice extent, the timing of sea ice retreat and, therefore, plankton production and growth (Coyle et al. 2011; Hunt et al. 2011). If the extent of sea ice is less with warming temperatures and ice-associated blooms do not occur in spring, the energy resources available for pelagic consumers would become more benthic dominated, and consequently, less available for juvenile Chum Salmon (Hunt and Stabeno 2002; Farley and Moss 2009; Farley et al. 2009; Hunt et al. 2011). As a result, continued monitoring of populations of Chum Salmon in the NBS and CS will lead to a greater understanding of how climate change will affect early marine growth and subsequent survival to the adult life stage.

### *Limitations*

Several caveats associated with this study may have limited our interpretation of the results. For example, the collection of juvenile Chum Salmon at only three stations in the CS in summers 2012 and 2013 may have contributed to the lack of contrast in the timing of marine entry and growth rate estimates for that region. Further, fish captured in the CS in 2007 were



larger than in 2012/2013, most likely because sampling in 2007 occurred in early to mid-September in the CS while sampling in 2012/2013 took place later in the growing season (early to mid-August). It is likely that not enough time had passed in 2012/2013 at the time of the CS survey for juvenile Chum Salmon to have moved from nearshore areas and, therefore, fish were not yet distributed at offshore stations by the time of sampling (J. Murphy, NOAA, personal communication). Similar patterns and timing of offshore movements over summer months have been documented for juvenile Chum Salmon outmigrating from the Yukon River in 2014, where outmigrating juvenile Chum Salmon were captured in the river delta in June/July, near the shore in August, and further offshore in the NBS in September (K. Howard, ADF&G, unpublished data).

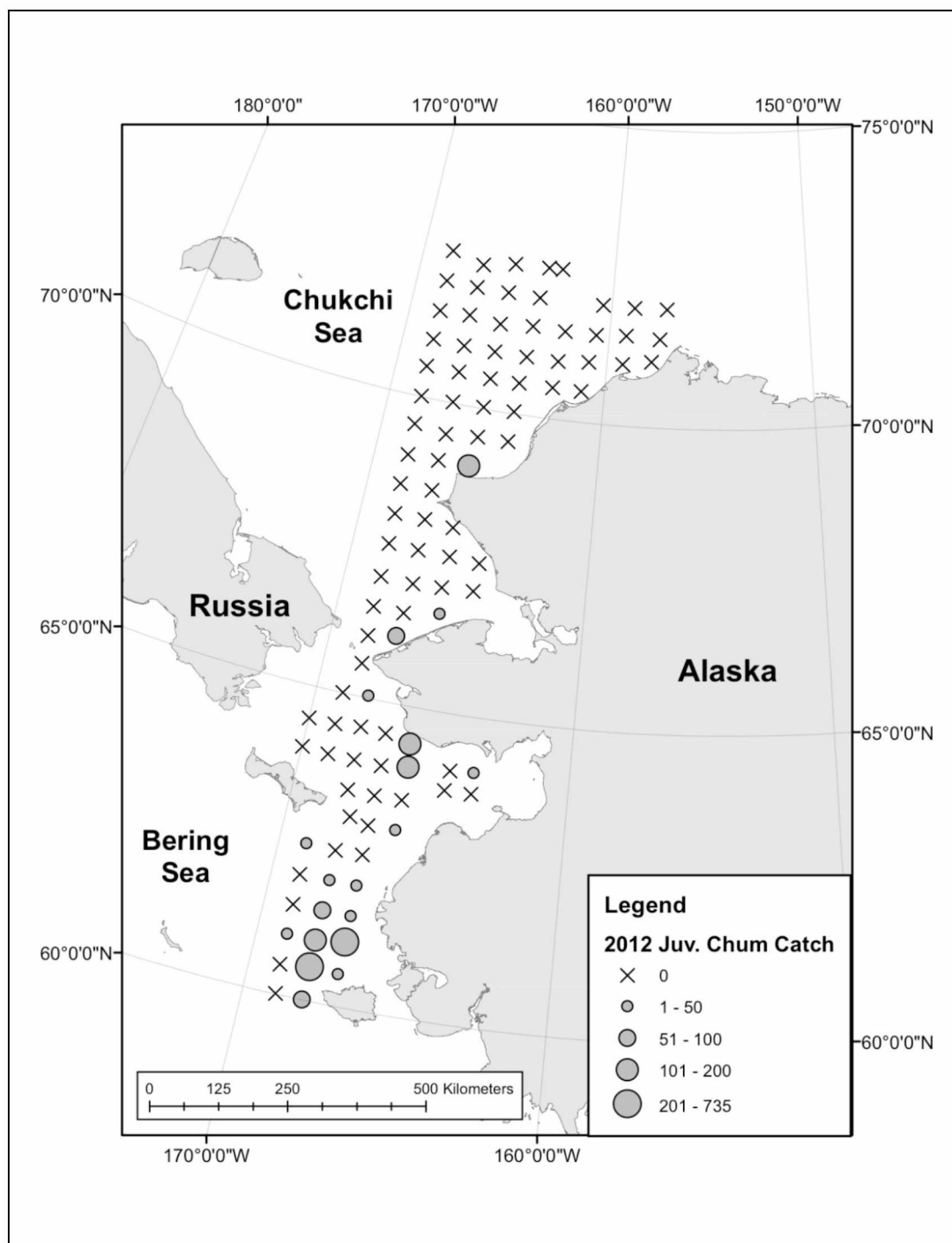
Another limitation on the comparisons of marine-entry timing and growth rates/body size was the loss of samples that were collected from the NBS in summer 2013 due to flooding on the research vessel. A total of 448 juvenile Chum Salmon (92-229 mm in length) collected from 26 stations in the NBS during the 2013 survey would have been the largest size range of the various region/year combinations examined in this study. These samples would have provided an additional opportunity to compare marine-entry timing and growth rates relative to the CS in summer 2013, a region/year combination with growth rates that were higher than all other region/year combinations. These data would have provided further clarification of how annual differences in environmental conditions might affect the marine-entry timing and growth rates of juvenile Chum Salmon in these two regions. These baseline data are important when evaluating the effects of climate-induced changes in these Arctic systems.

## *Conclusions*

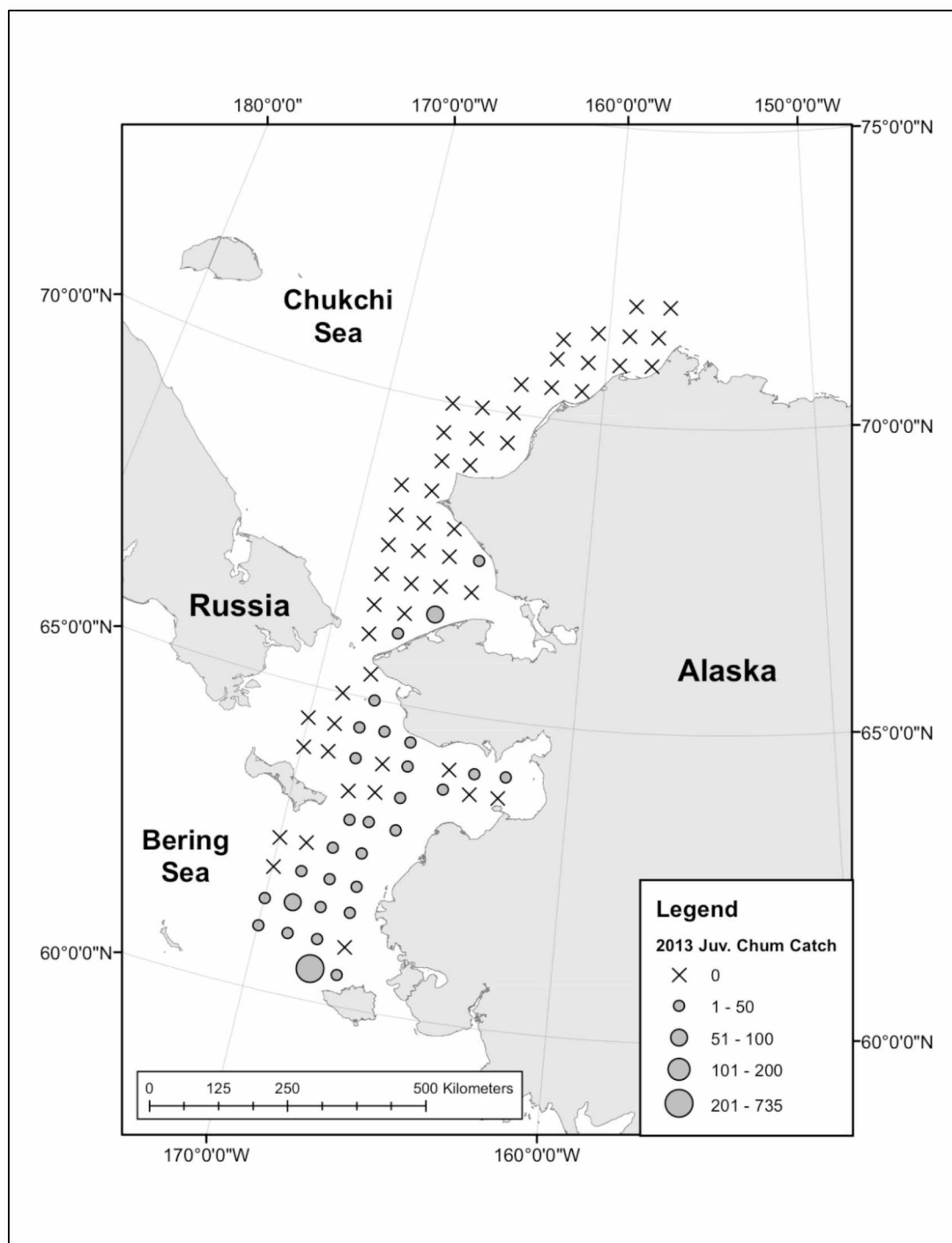
Changes in climate variability in the Arctic have the potential to alter key life-history stages of Pacific salmon stocks in Alaska, including entry to the marine environment and early marine growth. Warming oceans with higher SSTs during summer months have been shown to support higher marine survival rates and productivity for some Pacific salmon populations in the northeast Pacific, Gulf of Alaska, and the Bering Sea (Mueter et al. 2002; Mueter et al. 2005; Farley et al. 2007; Farley et al. 2009; Mantua 2009; Nielsen et al. 2013). While the relatively warmer SSTs might have positively influenced juvenile Chum Salmon growth in this study, the effects that warming temperatures may have on other factors such as marine-entry timing, prey availability, and survival during their first marine year are also important to understand within the context of climate change. Warming temperatures in freshwater environments might have significant effects on the outmigration timing of salmon smolts, leading to potential mismatches with optimal prey availability in nearshore marine environments (Tomaro et al. 2012; Satterthwaite et al. 2014). Earlier sea ice retreat that will likely accompany climate warming has implications on ice-associated productivity in the ocean, which influences prey composition and abundance, and competition for juvenile salmon in the Arctic and sub-Arctic (Stabeno et al. 2007; Coyle et al. 2011; Hunt et al. 2011). This complex suite of biotic and abiotic variables influence juvenile Chum Salmon early life history in the NBS and CS. As a result, it is critical to understand how these environmental conditions interact to impact early life stages and subsequent adult returns of Chum Salmon due to climate change in these regions.

Early marine life-history characteristics of juvenile Chum Salmon in this study were largely consistent among region and year combinations. These results suggest that juvenile Chum Salmon in the NBS and CS currently exhibit consistent marine-entry timing and growth

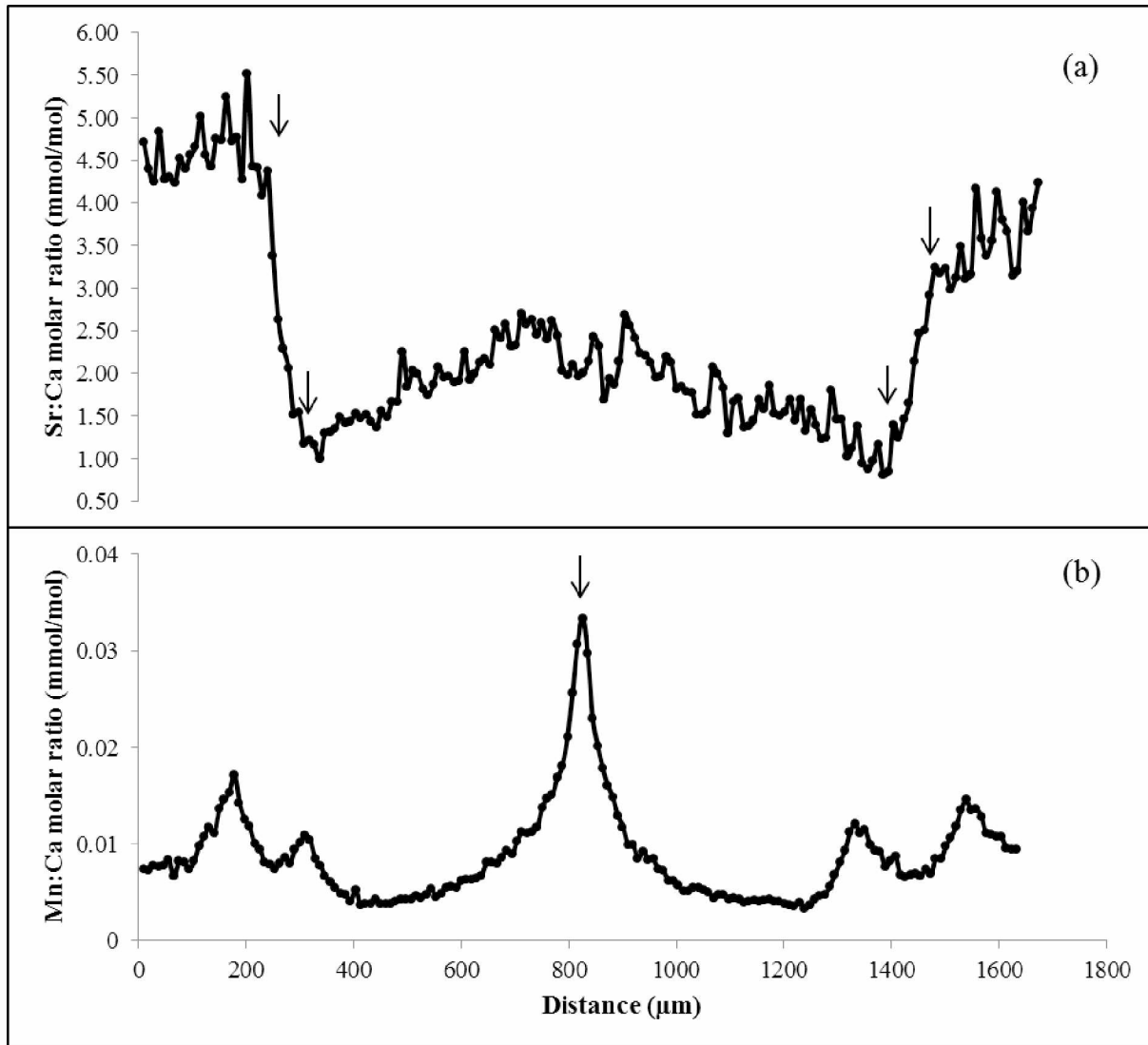
rates during their first marine summer, despite some differences in environmental conditions between regions and among years. Although it is expected that substantial sea ice will remain in these regions, altered timing of sea ice retreat and river ice break-up has uncertain consequences, not only on early life-history characteristics, but the productivity and carrying capacity of Pacific salmon in these systems (Sigler et al. 2011; Brown and Arrigo 2013). This study provides baseline data on early life-history attributes of juvenile Chum Salmon in the Alaskan Arctic, which will be important for future comparisons that assess the effects of climate-induced changes in these productive systems.



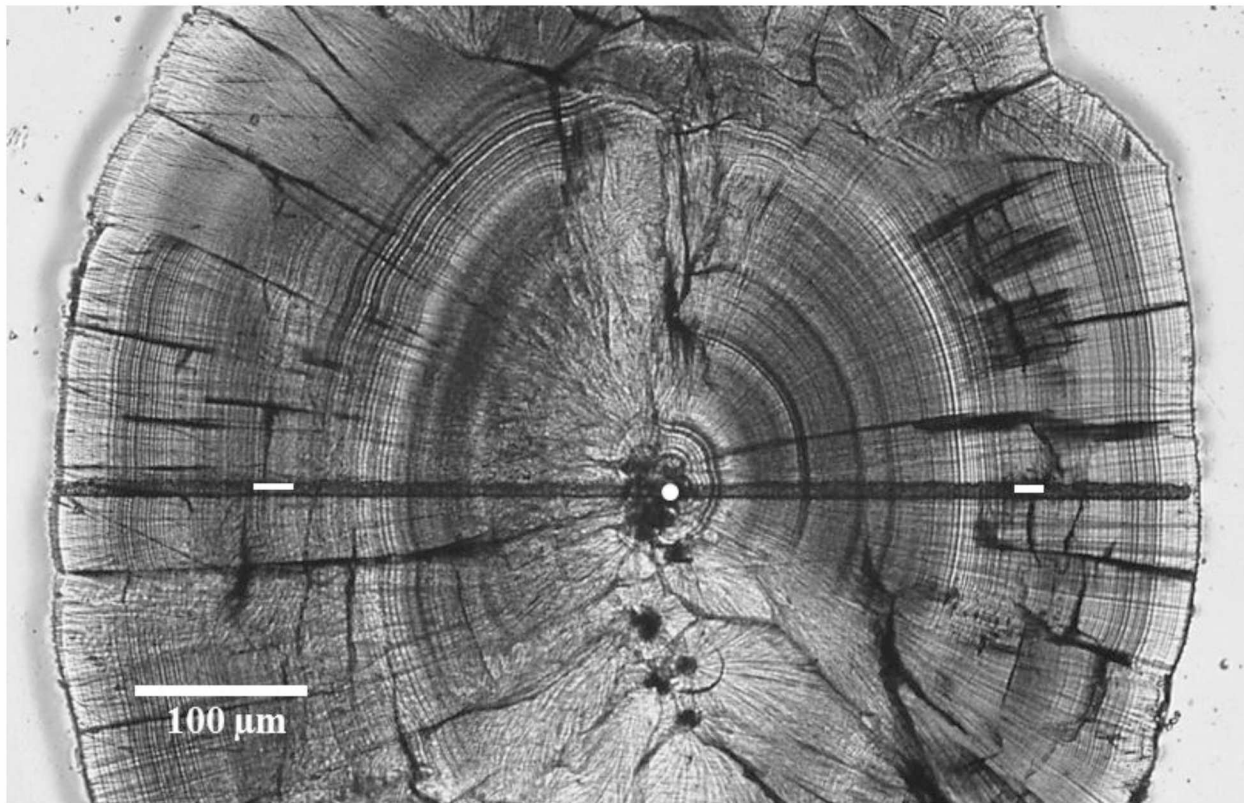
**Figure 1.** Catches of juvenile Chum Salmon during the 2012 Arctic EIS survey. Circle sizes represent catches for one 30-minute surface trawl at each station. Stations with an “X” denote locations where no juvenile Chum Salmon were caught. Reproduced with permission from NOAA.



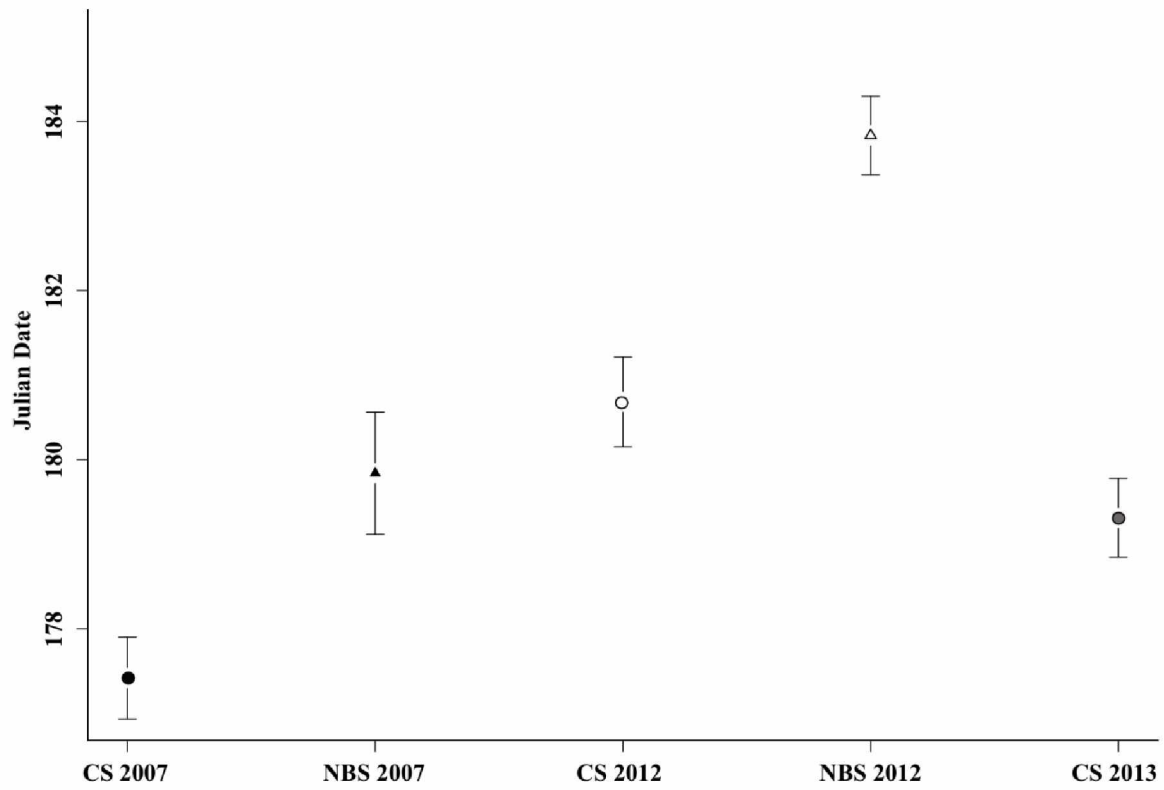
**Figure 2.** Catches of juvenile Chum Salmon during the 2013 Arctic Eis survey. Circle sizes represent catches for one 30-minute surface trawl at each station. Stations with an “X” denote locations where no juvenile Chum Salmon were caught. Reproduced with permission from NOAA.



**Figure 3.** Molar ratios of (a) strontium (Sr:Ca) and (b) manganese (Mn:Ca) along an ICP-MS transect of a juvenile Chum Salmon otolith. Arrows in the Sr:Ca plot indicate initial marine entry point and the point at which Sr:Ca ratios have reached fully marine levels. The arrow in the Mn:Ca plot indicates the chemical center of the otolith. This juvenile Chum Salmon (128 mm, 21 g) was collected on August 8, 2012 at latitude 66.000000°N and longitude -167.392288°W in the Chukchi Sea.

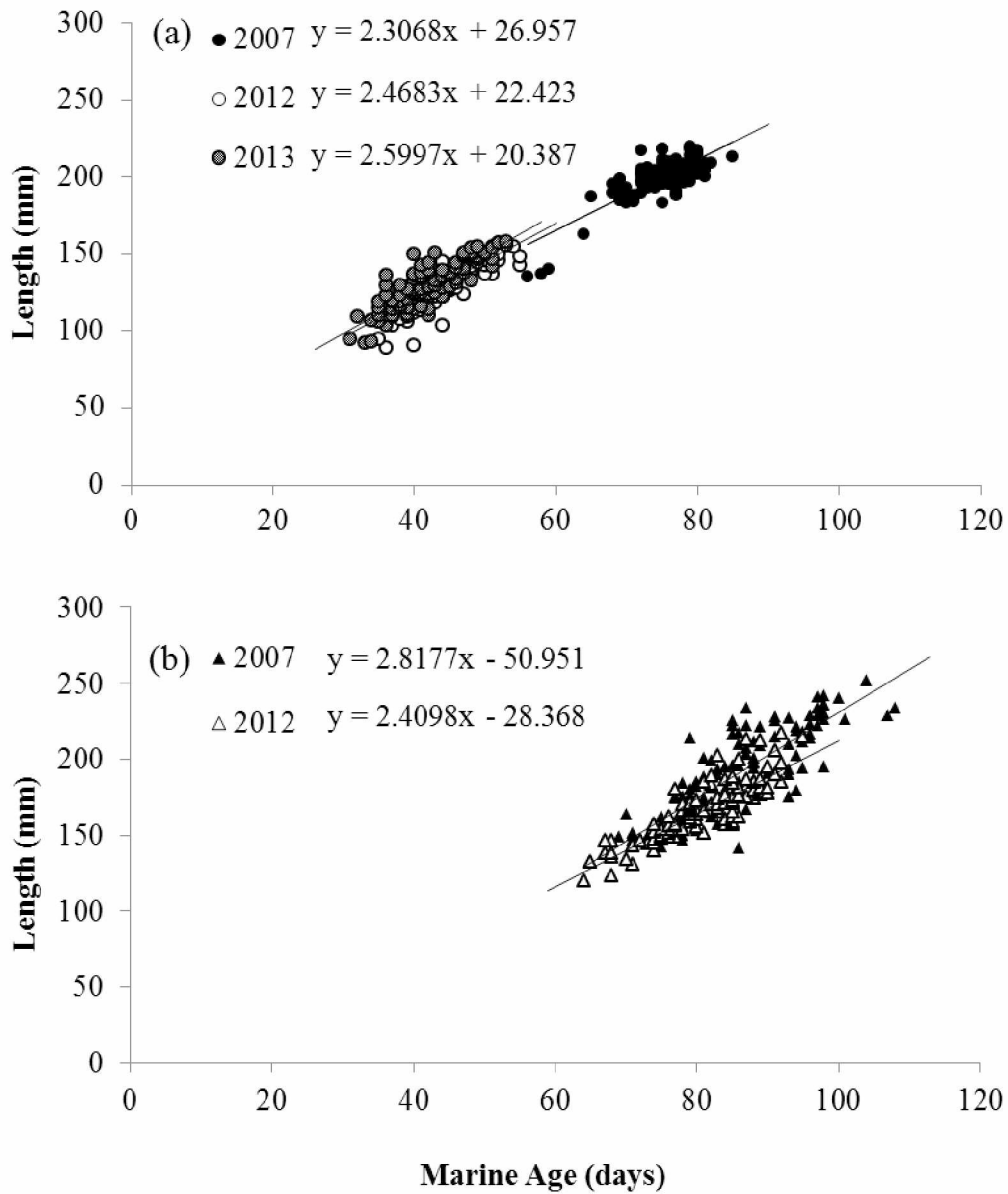


**Figure 4.** Cross section of a juvenile Chum Salmon sagittal otolith showing daily growth increments. White bars along the ICP-MS laser transect line (dark line through the core of the otolith) indicate the beginning and end of the sharp increase in Sr:Ca molar ratio, or the marine entry check. The chemical center (peak of Mn:Ca molar ratio) is indicated by the white circle. This juvenile Chum Salmon (128 mm, 21 g) was collected on August 8, 2012 at latitude 66.000000°N and longitude -167.392288°W in the Chukchi Sea.

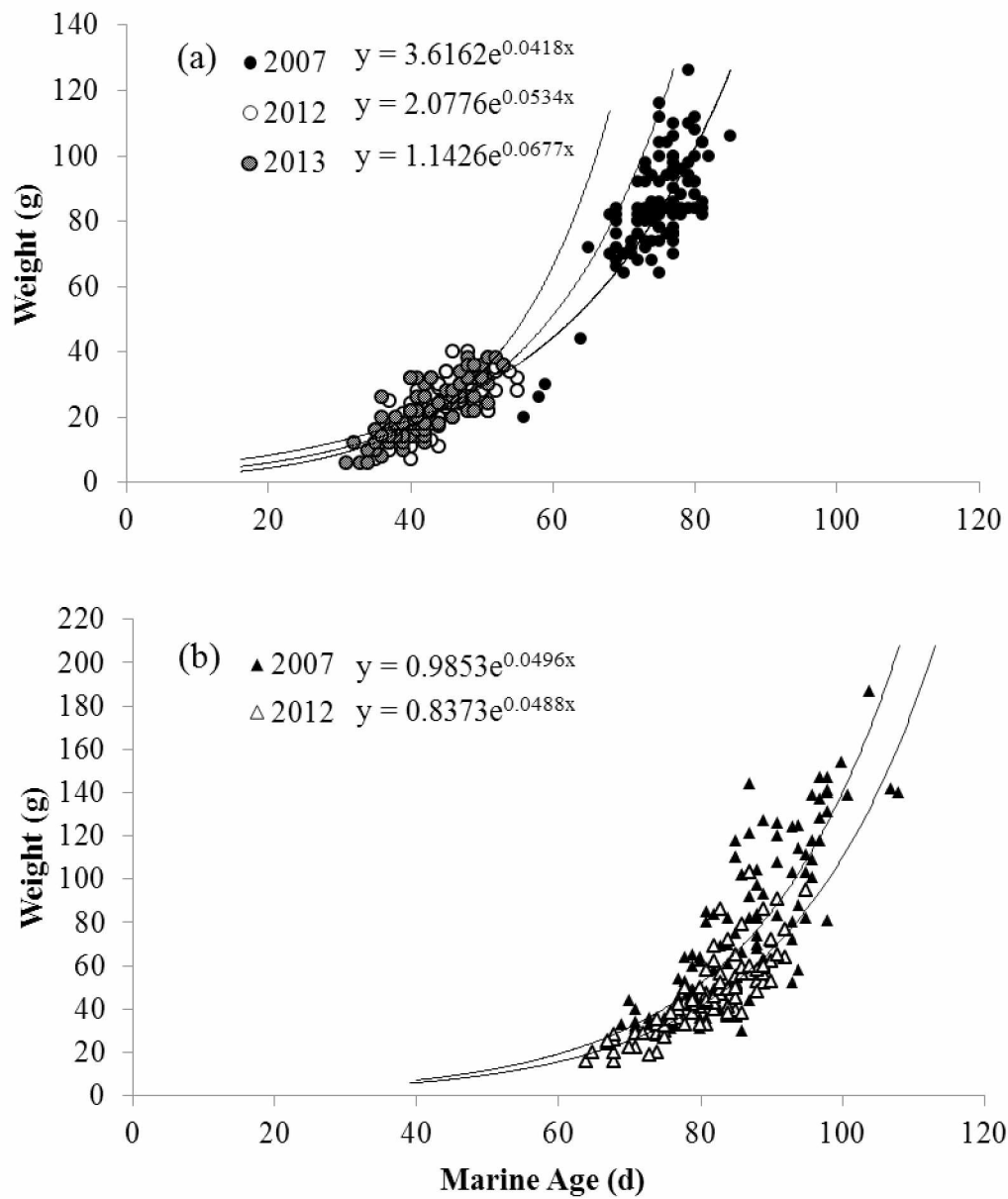


**Figure 5.** Mean entry date ( $\pm$  SE) of juvenile Chum Salmon for regions and years. Points correspond to Julian dates of 177, 179, 181, 183, and 179 for the Chukchi Sea in 2007 (CS 2007), the northern Bering Sea in 2007 (NBS 2007), the Chukchi Sea in 2012 (CS 2012), the northern Bering Sea in 2012 (NBS2012), and the Chukchi Sea in 2013 (CS 2013), respectively. These Julian dates correspond to calendar dates of June 26, June 28, June 29, July 1, and June 28 for CS 2007, NBS 2007, CS 2012, NBS2012, and CS 2013, respectively.





**Figure 6.** Linear regression models of fork length-at-age for (a) Chukchi Sea and (b) northern Bering Sea juvenile Chum Salmon. The slope coefficient in each equation indicates the growth rate of that particular region and year.



**Figure 7.** Exponential growth models of body weight-at-age for (a) Chukchi Sea and (b) northern Bering Sea juvenile Chum Salmon. The exponential term in each equation indicates the growth rate of that particular region and year.



**Table 1.** Length-frequency distributions of samples used in otolith aging analysis of juvenile Chum Salmon. Dashes (-) indicate that no fish were collected in that length bin in that region or year. Numbers with asterisks (\*) denote samples prepared, read, and analyzed by J. Murphy, NOAA, Juneau, Alaska. Note: NBS 2013 samples are not included due to a flooding event that occurred onboard in which all samples were either lost at sea or recovered and rendered unusable.

Fork Length Bin (mm)	Chukchi Sea			Northern Bering Sea	
	2007	2012	2013	2007	2012
80-100	-	3	3	-	-
101-120	-	18	25	-	-
121-140	3	54	40	-	9
141-160	-	23	25	23*	31
161-180	1	-	-	21*	46
181-200	45	-	-	23*	17
201-220	59	-	-	20*	6
221-240	-	-	-	22*	-
241-260	-	-	-	3*	-
Total	108	98	93	112*	109

**Table 2.** Number of surface trawl stations that yielded juvenile Chum Salmon, number of juvenile Chum Salmon collected from trawl hauls, number of otoliths used for aging, and number of otoliths used for chemical analysis from each region and year. Numbers with asterisks (\*) denote samples prepared, read, and analyzed by J. Murphy, NOAA, Juneau, Alaska. Note: NBS 2013 samples are not included due to a flooding event that occurred onboard in which all samples were either lost at sea or recovered and rendered unusable.

Region	Year	Stations	Total Fish	Otoliths Read	Otoliths Used
			Subsampled from all Stations		for Chemical Analysis
Chukchi Sea	2007	20	292	108	22
	2012	3	104	98	20
	2013	3	95	93	20
	Total	26	491	299	62
Northern Bering Sea	2007	36	559	112*	112*
	2012	16	480	109	20
	Total	52	1039	221	132

**Table 3.** Aging analysis of marine otolith increments for juvenile Chum Salmon. Fork length bin, number of otoliths analyzed, average marine increments, standard deviation, average entry date, and range of entry dates per length bin are listed by region and year. Dashes (-) indicate that no fish were collected in that fork length bin. Both calendar and Julian dates (in parentheses) are provided.

Region	Year	Fork	Weight	Mean	StDev	Mean	Mean	Minimum	Maximum
		Length	Range	Marine	Marine	Capture	Entry	Entry	Entry
		Bin (mm)	(g)	Increments	Increments	Date (Julian)	Date (Julian)	Date (Julian)	Date (Julian)
Chukchi Sea	2007	120-140	20-30	57.67	1.53	9/8 (251)	7/12 (193)	7/11 (192)	7/16 (197)
		141-160	-	-	-	-	-	-	-
		161-180	44	64.00	0.00	9/11 (254)	7/9 (190)	7/9 (190)	7/9 (190)
		181-200	64-86	73.16	3.57	9/9 (252)	6/28 (179)	6/22 (173)	7/7 (188)
		201-220	76-126	76.86	3.00	9/9 (252)	6/24 (175)	6/16 167)	7/1 (182)
		Mean		74.67			6/26 (177)		
	2012	80-100	7-12	37.00	2.65	8/12 (225)	7/6 (188)	7/3 (185)	7/10 (192)
		101-120	10-20	39.17	2.36	8/11 (224)	7/3 (185)	6/28 (180)	7/8 (190)
		121-140	14-34	43.26	2.93	8/11 (224)	6/29 (181)	6/22 (174)	7/7 (189)
		141-160	22-40	49.35	3.19	8/11 (224)	6/23 (175)	6/14 (166)	6/28 (180)
		Mean		43.75			6/29 (181)		

**Table 3, cont.**

	2013	80-100	6	3
		101-120	8-16	25
		121-140	18-30	40
		141-160	22-38	25
		Mean		
Northern Bering Sea	2007	140-160	30-44	23
		161-180	36-65	21
		181-200	58-86	23
		201-220	82-114	20
		221-240	110-154	22
		241-260	147-187	3
		Mean		
	2012	120-140	16-26	6
		141-160	19-43	31
		161-180	38-62	46
		181-200	50-79	17
		201-220	86-104	6
		Mean		

32.67	1.53	8/8 (220)	7/6 (187)	7/5 (186)	7/8 (189)
37.32	2.48	8/8 (220)	7/1 (182)	6/27 (178)	7/7 (188)
41.95	3.00	8/9 (221)	6/28 (179)	6/24 (175)	7/6 (187)
47.92	3.48	8/10 (222)	6/23 (174)	6/16 (167)	7/2 (183)
42.01			6/28 (179)		
76.61	4.52	9/18 (261)	7/4 (185)	6/24 (175)	7/12 (193)
80.67	5.49	9/23 (266)	7/2 (183)	6/22 (173)	7/12 (193)
86.22	5.13	9/24 (267)	6/30 (181)	6/20 (171)	7/14 (195)
89.40	4.88	9/23 (266)	6/26 (177)	6/12 (163)	7/11 (192)
95.27	6.27	9/24 (267)	6/21 (172)	6/10 (161)	7/1 (182)
99.75	3.79	9/29 (272)	6/18 (169)	6/14 (165)	7/1 (182)
85.88			6/28 (179)		
68.33	3.04	9/16 (260)	7/9 (191)	6/30 (182)	7/17 (199)
76.74	4.57	9/17 (261)	7/2 (184)	6/27 (179)	7/8 (190)
83.22	3.87	9/22 (266)	6/30 (182)	6/25 (177)	7/7 (189)
86.94	3.52	9/23 (267)	6/28 (180)	6/23 (175)	7/4 (186)
89.38	4.18	9/24 (268)	6/26 (178)	6/21 (173)	7/4 (186)
81.08			7/1 (183)		



**Table 4.** Tukey HSD (honest significant difference) multiple comparisons of marine-entry dates of juvenile Chum Salmon across regions and years. CS = Chukchi Sea, NBS = northern Bering Sea, and the corresponding number represents the sampling year. Asterisks (\*) indicate a significant difference between region/year groups.

	Estimate	SE	t value	p value	
CS12-CS07	3.264	0.778	4.197	<0.001	*
CS13-CS07	1.895	0.789	2.401	0.117	
NBS07-CS07	2.443	0.753	3.219	0.012	*
NBS12-CS07	6.171	0.758	8.145	<0.001	*
CS13-CS12	-1.372	0.808	-1.698	0.436	
NBS07-CS12	-0.844	0.772	-1.094	0.810	
NBS12-CS12	2.904	0.777	3.738	0.002	*
NBS07-CS13	0.528	0.783	0.674	0.962	
NBS12-CS13	4.275	0.788	5.428	<0.001	*
NBS12-NBS07	3.748	0.751	4.992	<0.001	*

**Table 5.** Tukey HSD (honest significant difference) multiple comparisons of coefficients for juvenile Chum Salmon weight-at-age relationships across regions and years. CS = Chukchi Sea, NBS = northern Bering Sea, and the corresponding number represents the sampling year. Asterisks (\*) indicate a significant difference between region/year groups.

	Estimate	SE	t value	p value
CS12-CS07	0.005	0.003	1.378	0.169
CS13-CS07	0.019	0.004	5.226	<0.001 *
NBS07-CS07	0.003	0.003	0.967	0.334
NBS12-CS07	0.003	0.003	1.033	0.302
CS13-CS12	0.014	0.004	3.984	<0.001 *
NBS07-CS12	0.002	0.003	0.775	0.439
NBS12-CS12	0.002	0.003	0.609	0.542
NBS07-CS13	0.016	0.003	5.540	<0.001 *
NBS12-CS13	0.016	0.003	5.171	<0.001 *
NBS12-NBS07	0.000	0.002	0.176	0.860

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## General Conclusions

This study has expanded the current knowledge related to the early marine life-history characteristics of juvenile Chum Salmon *Oncorhynchus keta* in the NBS and the CS. The timing of marine entry and growth rates of juvenile Chum Salmon were estimated using otolith aging and inductively coupled plasma mass spectrometry chemical analyses. Marine-entry timing for the stocks sampled in this study ranged from mid-June to mid-July, with some variation between regions and among years. Marine age coupled with fork length and body weight data provided estimates of growth rate for each region/year combination. Weight-at-age growth rates were consistent between regions and among years, with the exception of juvenile Chum Salmon in the CS in 2013, which had a significantly higher growth rate than all other region/year combinations. In addition to increasing the understanding of early marine ecology of Chum Salmon, this thesis can serve as a baseline with which future studies in Arctic and sub-Arctic regions can be compared.

Little is known about the early marine life-history characteristics of juvenile Chum Salmon in western Alaska. The first marine summer is a critical period for Pacific salmon that, in part, determines the success of cohorts that survive to adulthood (Sogard 1997; Beamish and Mahnken 2001; Moss et al. 2005; Farley et al. 2007; Wertheimer and Thrower 2007). Outmigration timing of juvenile Chum Salmon is dependent on many abiotic factors, including river ice break-up timing, water temperature, and day length (McCormick et al. 1998; Jutila et al. 2005; Jensen et al. 2012). Predicted warming temperatures and timing of river ice break-up in the Arctic have implications on arrival timing to the marine environment, and therefore, prey availability for juvenile Chum Salmon. Changes in river ice break-up timing and hydrology caused by climate change may alter juvenile Chum Salmon outmigration timing in Arctic and

sub-Arctic regions, which could cause mismatches between marine-arrival timing and optimal food resources (Crozier et al. 2008; Grebmeier 2012; Tomaro et al. 2012; Satterthwaite et al. 2014). Therefore, altered outmigration timing can lead to lowered survival of juvenile Chum Salmon, and subsequently, lower adult returns.

The consistent timing of marine entry in both the northern Bering and Chukchi seas suggests that outmigration timing in both systems may be a phenological adaptation to allow for the greatest utilization of resources during the short growing season at high latitudes (Holtby et al. 1989; McCormick et al. 1998; Tomaro et al. 2012; Miller et al. 2014; Satterthwaite et al. 2014). However, greater variation in distance traveled downstream by Chum Salmon smolts, as well as in river ice break-up dates, are likely reasons for higher observed variability in marine-entry timing of juvenile Chum Salmon from tributaries of the NBS rather than the CS. These findings suggest that future outmigration studies should be conducted over a longer time period and coupled with river of origin and diet studies. This will provide important fine-scale information on the early life history of Chum Salmon in these Arctic regions and how they might be affected by climate change.

Climate variation and its impact on the marine environment play an important role in the growth and production of Pacific salmon in Alaska and must be considered when investigating trends in primary/secondary production and salmon abundance (Beamish and Bouillon 1993; Farley et al. 2007). Changes in seasonal sea ice extent in the Bering Sea may affect juvenile salmon indirectly through changes in primary and secondary production in nearshore environments (Stabeno et al. 2007; Farley et al. 2009; Hunt et al. 2011; Prowse et al. 2011). Relatively late sea ice retreat in the NBS is characterized by ice-associated phytoplankton blooms that produce large, lipid-rich copepods for pelagic consumers, such as juvenile Pacific

salmon (Hunt et al. 2011; Brown and Arrigo 2013; Prechtl 2014). It appears that currently, warmer SSTs in the NBS and CS seem to be favorably affecting juvenile Chum Salmon growth rates (Moss et al. 2009). However, continued warming in these regions may decrease food availability for juvenile Chum Salmon in the Bering Sea which, in turn, might encourage northward movement of southern stocks into more favorable areas such as the CS (Moss et al. 2009; Murphy et al. 2009; Sigler et al. 2011; Brown and Arrigo 2013; Prechtl 2014). Other mechanisms to growth and survival of juvenile Chum Salmon must be explored with respect to a changing climate and are important in understanding future recruitment of adults into fisheries.

Adult Chum Salmon are a highly valued fish species that are targeted mainly in commercial and subsistence fisheries in Alaska. For example, in 2012, the commercial harvest of Chum Salmon in Alaska in 2012 reached over 63,000 metric tons valued at over \$93 million USD, making Chum Salmon the most monetarily valuable commercial salmon species in Alaska (NOAA 2015). Chum Salmon are currently at the forefront of Alaskan fisheries management due to declining Chinook returns in the Arctic-Yukon-Kuskokwim (AYK) region, as well as their importance in subsistence fisheries in western Alaska (Wolfe and Spaeder 2009; Eggers et al. 2013). Chum Salmon are important in Alaskan fisheries and continued value should be placed on research of this species to inform managers of changes in juvenile life-history patterns, as these regions are expected to be affected by climate change. Understanding the early life-history characteristics and factors that influence growth and survival of Chum Salmon are of the utmost importance to managers, hatchery producers, and subsistence fishermen in Alaska.

Planned oil and gas development in high Arctic regions could have negative implications for marine species such as Chum Salmon. Currently, regions in the CS that are hypothesized to be used as migratory pathways by juvenile Chum Salmon from the Canadian Arctic (Craig and

Haldorson 1986; Irvine et al. 2009) are being leased and developed for oil and gas extraction (Holland-Bartels and Pierce 2011). Previous research indicated that areas in the Yukon River delta platform, mudflats, and tidal sloughs were most vulnerable to potential oil spills in Norton Sound exploratory drilling in the 1980s (Martin et al. 1987). Therefore, juvenile Chum Salmon are vulnerable to oil exploration in these environments in the NBS and CS, and should be considered with respect to future drilling in the Arctic.

As one of the few salmon species that may be resilient to future climate warming due to their minimal freshwater residency period and their ability to utilize cooler waters at more diverse latitudes, Chum Salmon are an important species to monitor in relation to climate warming (Craig and Haldorson 1986; Irvine et al. 2009; Sigler et al. 2011). It is difficult to obtain a comprehensive examination of mechanisms that affect outmigration timing and growth of juvenile Chum Salmon in these Arctic and sub-Arctic systems due to the many complex biotic and abiotic factors that affect this life-history period. Future sampling in both the NBS and CS should occur in September to allow for fish to be caught in offshore stations. A thorough understanding of both freshwater and marine environmental variables that affect juvenile Chum Salmon growth and survival, including water temperature, sea ice retreat timing, and food availability, would further tease out causal mechanisms associated with the complex early life-history patterns of juvenile Chum Salmon. It is recommended that information on marine-entry timing be collected in successive years and over a longer time period to evaluate real differences among region/year combinations. This information could then be used to correlate any changes in marine-entry timing to environmental factors that might influence growth and survival. Genetic analyses to estimate stock-of-origin would also be beneficial for detailed information on the downstream distance traveled and stock-specific outmigration timing of these juvenile Chum

Salmon populations. Detailed analyses such as these will also aid in determining if growth rates and marine-entry timing are locally adapted traits and/or vary with different life history forms in these high-latitude populations. The results of this study suggest that further monitoring be used to better understand the dynamics of the NBS and CS ecosystems with respect to juvenile Chum Salmon early life-history characteristics in a changing climate. Due to climate models predicting high latitudes of the NBS and CS to be greatly affected by continued warming, the benchmark of early marine life-history characteristics which this thesis provides is critical for important commercial species such as Chum Salmon.

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